12TH CANADIAN CONFERENCE ON EARTHQUAKE ENGINEERING
JUNE 17-20, 2019
CHÂTEAU FRONTENAC
QUÉBEC, QC.
12ÈME CONFÉRENCE CANADIENNE DU GÉNIE PARASISMIQUE
17-20 JUIN 2019
CCEE 2019

Framework for Integrating Design and Assessment in Performance-Based Seismic Design of Buildings

Joaquin Acosta[1], Siriwut Sasibut[3], Feng Rong[4], Oh-Sung Kwon[2]

[1] Graduate Student, Department of Civil & Mineral Engineering, University of Toronto - Toronto, ON, Canada.
[2]Associate Professor, Department of Civil & Mineral Engineering, University of Toronto - Toronto, ON, Canada.
[3] Research Engineer, Software Development & Support, S-FRAME Software Inc. - Richmond, BC, Canada.
[4]Senior Research Engineer, Software Development, S-FRAME Software Inc. - Richmond, BC, Canada.

ABSTRACT

Performance-Based Seismic Design (PBD) has been increasingly applied to the design and retrofit of buildings around the world in recent years. This has been possible due to ongoing research on PBD conducted since mid-1990s, growing computing power, and development of numerical models that can simulate nonlinear structural behavior. There exist guidelines developed by expert committees of researchers and practitioners (e.g. *Tall Buildings Initiative* guidelines by PEER [1]) that propose minimum requirements for projects using a PBD approach, including modeling methods, analyses procedures, and performance criteria. PBD methodologies commonly share the essential steps of: 1) performing the design of the structure, typically done using an elastic analysis model (design model), and 2) assessing its performance by means of nonlinear analysis. The assessment step can be very cumbersome due to the amount of time and expertise required to develop a nonlinear model, running analyses and the subsequent post-processing of data, which can prevent a broader adoption of the approach by design offices. Furthermore, the volume of information on nonlinear modeling of structural components is vast and widespread among many publications. Hence, it could take time and efforts for an engineer to select computationally efficient yet practically accurate numerical models for every structural component in the structure. To facilitate this step, this paper explores the formulation of a framework that integrates design and assessment by using an elastic design model, developed with a commercial platform, S-FRAME, as input for the semi-automatic generation of a nonlinear model, which is built upon the choices made by a user. A nonlinear model for a given structural element is selected after consulting an up-to-date collection of modeling approaches for typical structural components. This framework allows the user to focus on the important task of choosing the most suitable model for the structural components involved, while avoiding cumbersome work when defining and post-processing the model, which can be automated. OpenSees [2] is used as the nonlinear analysis engine. The framework is illustrated through a steel building example.

Keywords: nonlinear modeling, performance-based seismic design, steel MRF, modeling automation, expert-system.

1 INTRODUCTION

1.1 Overview of Performance-Based Seismic Design

The concept of Performance-Based Seismic Design (PBD) has been widely discussed in literature and employed in structural design practice since mid-1990s [3]. In the conventional design approach, engineers evaluate force demands for each structural member based on linear elastic analysis of a structural system. Then, the structural members are proportioned such that the force capacities of the members are greater than the force demands obtained from analysis. Because most building structures are designed to behave in the inelastic range under design seismic loads, various response modification factors, such as strength reduction, over-strength, and displacement amplification factors, are used to consider the inelastic response of the structure [4]. While the conventional design approach includes performance requirements, such as life safety (i.e., force capacity) and serviceability (i.e., drift limit), linear elastic analysis cannot realistically assess the performance of a structure subjected to earthquake excitations. In addition, conventional code-complying prescriptive design is limited in meeting an owner's various performance needs such as the expected economic loss associated with a certain earthquake event intensity.

In the PBD approach, on the other hand, target performance requirements for various seismic hazard scenarios are defined, and a structure is designed to meet the requirements. There are guidelines developed by expert committees of researchers and practitioners (e.g. *Tall Buildings Initiative* by PEER [1], *Alternative Procedure* by LATBSDC [5]) that propose minimum requirements for projects using a PBD approach, including modeling method, analysis procedures, performance criteria, and the level of expertise in nonlinear structural behavior required for performance assessment. Figure 1-1 shows the typical steps in a PBD design process. The first two steps are common to prescriptive procedures and the design is typically carried out using user-friendly structural analysis software packages that integrate linear elastic modeling and design according to many building design codes for various structural materials (e.g. S-FRAME [6], ETABS [7]). Steps 3 to 5 correspond to the PBD assessment task, where a numerical model for nonlinear analysis is built based upon the structural details generated in the previous design tasks (*database of design details*). The assessment step can vary in complexity from a local and global evaluation of deformations and force demands against capacities based on nonlinear pushover analysis to a full probabilistic evaluation of economic loss based on dynamic time-history analyses. Regardless of the specific methodology being applied, steps 1 through 5 are essential.

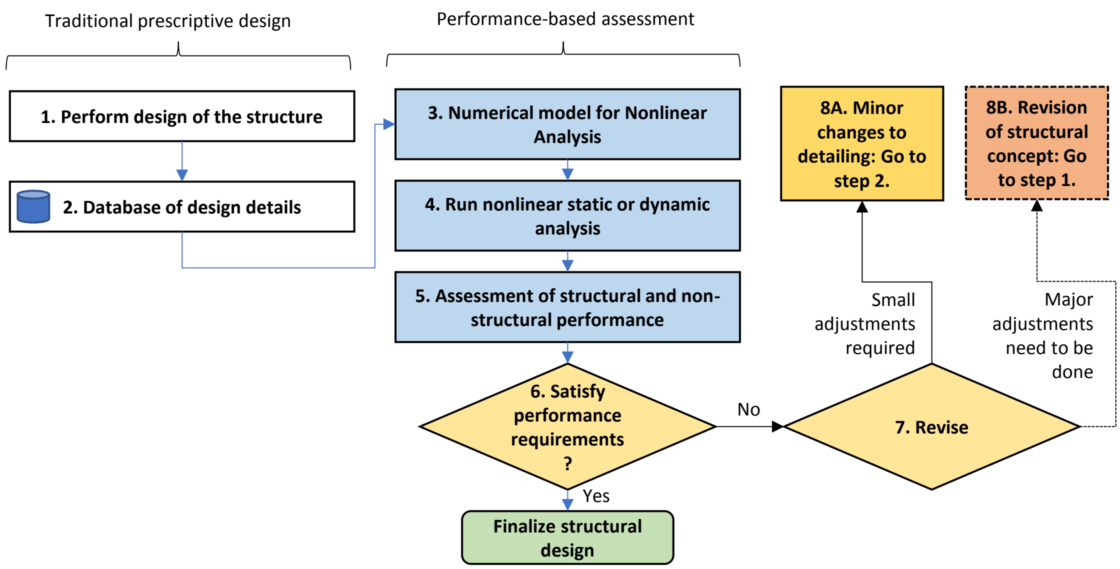


Figure 1-1. Overall design process in Performance-Based Seismic Design of buildings.

1.2 Nonlinear Analysis for Performance Assessment

The performance of a structure needs to be assessed based upon a realistic numerical model that can capture its inelastic behavior up to failure. For this purpose, it is a common practice for engineers to build a whole new model, in a different specialized software, to carry out nonlinear analysis. Developing a numerical model for nonlinear analysis thus requires significant engineering time and effort. Even though nonlinear analysis has been extensively used in research projects, there is no widely-accepted or standardized numerical modeling method for nonlinear analysis, which was indicated as one of the main barriers in adopting nonlinear analyses in design practice [8], [9]. Only in recent years have major funding agencies and research centers in the U.S. invested consorted efforts to develop guidelines for performance-based design in which a significant portion of the documents are allocated for modeling and analysis methods [10]–[12]. Nevertheless, there still exists a significant gap between the latest developments in the performance assessment method of a nonlinear structure, and the analysis and design process in structural engineering practice.

1.3 Objectives of this Research

This project aims to bridge an existing gap between the body of knowledge on structural modeling for seismic performance assessment available in research and the practical use of these models by the engineering profession. Two specific objectives are:

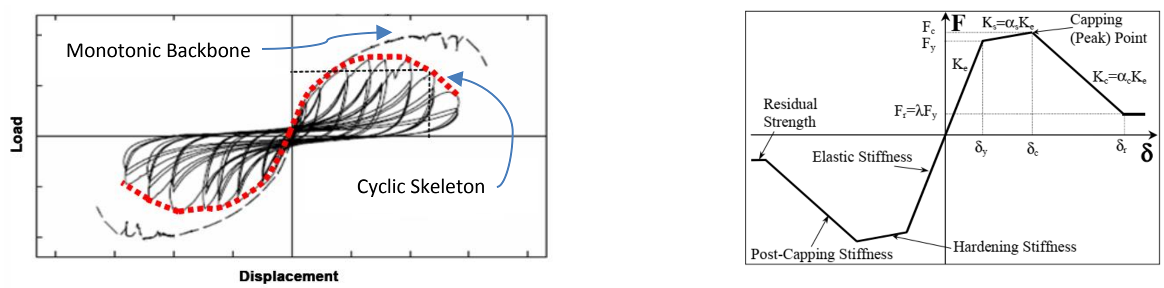
i. To develop a knowledge base of nonlinear models of structural components considering the state of the art in structural engineering. This knowledge base can be used by engineers to find and review appropriate component models to develop a nonlinear model of a building system.
ii. To develop an expert-system which can facilitate the nonlinear model generation process of a structure by accessing the knowledge base. For a given structure, the expert-system will take advantage of an available elastic model developed with S-FRAME structural analysis and design software, as a starting point for developing a nonlinear model for performance assessment.

In the following, a review of currently available guidelines for nonlinear modeling of structural components is presented. A brief discussion of selected models for components in steel moment resisting frames (MRFs) is included. Finally, the proposed framework is described and an example of a steel MRF building is shown.

2 NONLINEAR MODELING OF STRUCTURAL COMPONENTS

2.1 Review of Available Guidelines on Nonlinear Modeling for Performance Assessment

Only recently, efforts have been made to develop guidelines on modeling the nonlinear response of structural components for their assessment in a PBD setting, such as the PEER/ATC Modeling Guidelines [10] which provide guidance for modeling and performing assessment of frame and shear wall structural systems for tall buildings, or the most recent guidelines from the ATC-114 Project by NIST [13], that provide updated information for a broader spectrum of structural systems. An important concept that has been extensively used is the *backbone* curve, defined for a given structural component as a reference force-deformation curve that envelopes all possible hysteretic paths of responses as shown in Figure 2-1(a). The backbone curves are further categorized as monotonic or cyclic, depending on the type of experimental response they are referring to. In the figure, the two types of backbone curves are defined on top of experimental hysteretic responses: the *monotonic backbone* refers to the monotonic test and the *cyclic skeleton* corresponds to the envelope of cyclic responses.



(a) (b)

Figure 2-1. Backbone curve: (a) monotonic and cyclic backbones [10], (b) schematic definition [14].

In Figure 2-1(b) a backbone curve is depicted schematically. The ranges comprising the curve are an elastic one up to a yield force, a post-yield range up to a cap in strength, and a decaying branch that reaches a residual strength segment, after which total loss of resistance should be assumed. The descending portion of the backbone curve represents deterioration and plays an important role in performance assessment. For example, using single degree of freedom (SDOF) and multi-degree of freedom (MDOF) frame models, Ibarra and Krawinkler [14] concluded that collapse capacity is most sensitive to this post-capping slope and the deformation at which it starts. Therefore, the incorporation of deterioration into component models is essential for assessing the response of structures under excitations that are likely to cause damage, such as ground motions at the level of a *Maximum Considered Earthquake* (MCE). The most realistic option to include cyclic deterioration in analysis is to account for it explicitly in the model formulation, and so the model could replicate any hysteretic behavior depending on the loading (*adaptive* model). On the other hand, the simplest but least accurate is the option of neglecting cyclic deterioration in the model. In that case the analyses are valid only up to a certain deformation level. An option in between is to use a cyclic backbone that has some level of deterioration and omit the analytical modeling of cyclic damage; the backbones found in the ASCE 41 standard [15] are of this type. It is important to recognize that the first option is suitable for dynamic analysis only, but not for static pushover analysis given that cyclic behavior is not considered in this kind of analysis. The other options include cyclic deterioration in an implicit manner and are more suitable for static pushover analysis, but they can be used for dynamic analysis as well.

The simulation obtained using a nonlinear model of a given component should match the median response of an actual structural component. To achieve this, backbones curves and/or model parameters should be calibrated to match representative available experimental tests results [10]. Recently, NIST published a series of guidelines [11], [16]–[18] with updated recommendations to define monotonic and cyclic backbone curves of several structural components of steel and RC moment resisting frames, RC shear walls, wood panels, and other systems, that are based on extensive review of experimental results accumulated up to this date. These curves represent an update of previously available backbone curves, such as the ones found in ASCE 41, and are meant to be used as a reference for calibrating hysteretic models.

Nonlinear modeling approaches of structural components can be classified according to the distribution of inelasticity throughout the component [12]. On one end of the spectrum are concentrated plasticity (CP) models, which are conceptually simple and numerically efficient but need calibration. Continuum finite element models (FE) are on the opposite end of the spectrum, that need less calibration but are computationally expensive. Distributed plasticity formulations (DP), such as a fiber-section models, are between the CP and FE modelling approaches. Given the common assumption that plane sections remain plane after loading, the DP model is not feasible to model tridimensional effects such as local buckling or lateral-torsional buckling of the element unless the uniaxial stress-strain law is modified, and the model is calibrated against test data or detailed FE analysis results.

2.2 Overview of Models for Typical Components in Steel Moment Resisting Frames

A model that has been extensively used in research is the modified Ibarra-Medina-Krawinkler (IMK) model, which is a CP model for beams and columns with a multilinear backbone capable of modeling cyclic deterioration under any type of loading protocol [19], [20]. It has been calibrated by Lignos and Krawinkler [21] against a database of test specimens including wide-flange beams, and HSS columns. They provide sets of equations to calculate each model parameter based on the geometry and material properties of the steel component being modeled and it has been implemented in the OpenSees platform [2]. The model represents the moment-chord rotation response, without any interaction with other component responses. Hence, for beam-columns, moment capacity needs to be adjusted *a priori*.

There are fiber-section models for beams that include cyclic deterioration, such as the one proposed by Bosco and Tirca [22] for wide-flange beams, in which they used a low-cycle fatigue failure model wrapped around the uniaxial constitutive law to account for the net effect of all cyclic damage modes. The model was calibrated to match experiments of beams that experienced mainly flange local buckling, with very good agreement. The reported results are for wide-flange beams with a low web slenderness ratio subjected to standard symmetric ramped displacement protocols. For columns, a fiber-section approach with a simple bilinear material model without deterioration has been used to model the response of stocky W14 and similar column sections [23], based on the stable behavior that heavy sections present, for which local buckling appears only at large deformations. For shallower wide-flange section profiles it has been indicated that cyclic deterioration can have a major effect and should be incorporated in analysis [16].

To model the panel zone in beam-to-column steel connections, a well-known CP model was developed by Gupta and Krawinkler [24] using a parallelogram comprised of rigid trusses and a rotational spring whose response is in terms of shear force-shear distortion of the panel zone. Parameters to define its backbone can be found in [11]. Guidance to build the model is given in the context of 2D analysis.

3 PROPOSED FRAMEWORK

3.1 Automation of Nonlinear Modeling of a Structural System

To overcome the complexity involved in developing a nonlinear model, performing analysis, and post-processing of results, different strategies have been proposed. Psyrras and Sextos [25] proposed an expert-system to develop the nonlinear model of an RC building and perform analysis and assessment with minimum user effort. The program is limited to an RC structural system with orthogonal geometry and the modeling approaches for structural components are fixed. Chen and Kao [26] developed an expert system to help engineers to build nonlinear models. Their system includes a database of nonlinear models of structural components that can be queried to find available models for different structural components. Provided the geometry of the building is fully defined, the system allows for automatic generation of building component models in a generic XML format that could potentially be used to generate model files for any nonlinear structural analysis package that accepts script input, provided the models are implemented in the package.

Given that a detailed elastic design model is commonly prepared in order to design a building structure, the task of defining a nonlinear model of the same building in a different specialized software affects productivity by requesting the user to model the structure again, replicating geometry and gravity loading. Additionally, not every component of a building needs to be modeled as a nonlinear element for performance assessment—as per current methodologies [5], [15], some components that are categorized as force-controlled are supposed to remain elastic, even for MCE ground motions—hence they do not need further refinement in the modeling. Therefore, it is highly desirable that a PBD framework can integrate the geometry defined in the elastic model and avoids duplication of modeling efforts. Furthermore, often the type of nonlinear models used in a building model are constrained within the library of models of the software being used. Proprietary software is not easily kept updated with the latest findings from research nor it can be modified by users. If PBD means applying the state of the art in structural engineering, then it is desirable for practicing engineers to have access to the latest proven models that are available. On the other hand, having just a list of models that can be used to model a certain structural component is not enough to build confidence on the nonlinear model being developed [9]. Tools are needed to efficiently validate a nonlinear model. This can be done by facilitating comparisons of simulated response against experimental data and performing tests with different model parameters to see their effect, as it can be done for brace modeling in concentrically braced frames using the application developed by Simpson et al. [27].

In the proposed framework, the above issues are addressed by:

i. Using the geometry of the structure defined by the elastic design model. Adjustments are done where needed for the formulation of nonlinear models.

ii. Redefining only the components that are meant to be nonlinear.
iii. Lumping components that are to remain elastic into a compound elastic part, hence they are defined only once, in the design model.
iv. The nonlinear model to be used for a given structural component is selected from a knowledge base, after its validation by the user.

The model validation step consists of selecting a model from a list that the knowledge base will present based on the structural component type (beam, column, etc.) and evaluating its simulated response as compared to available test results. The user can modify model parameters and recheck the calculated response to understand parameters effects. If the model is deemed satisfactory, then the modeling details are written automatically by the program. Hence, once all nonlinear components have been reviewed and have and assigned model, the system writes a script that can be sourced into OpenSees for analysis

OpenSees [2] was chosen as the nonlinear analysis program because it is open source and because is being constantly updated with the latest models developed by researchers. The framework has been implemented using the Python programming language [28], following an object-oriented approach.

3.2 Overall process

Considering the process of PBD in Figure 1-1, steps one through three are further detailed in Figure 3-1. The proposed framework is concerned with the third step, namely the development of the nonlinear model. As shown, three key sub steps are defined:

A. The user specifies components in a building elastic model that will be modeled using a nonlinear model
B. If a component is elastic, no further action is required and the component properties (stiffness, mass and loads) are lumped into a compound elastic part that is represented through global stiffness and mass matrices, and a force vector. If a component is expected to behave in the inelastic range, then a subprocess starts where the user can select a model from the knowledge base, validate its behavior by comparing simulation result against experimental response, and accept the model or try a different one until all elements have been covered.
C. The nonlinear analysis model, comprised of the elastic compound part and the nonlinear elements, is generated for analysis.

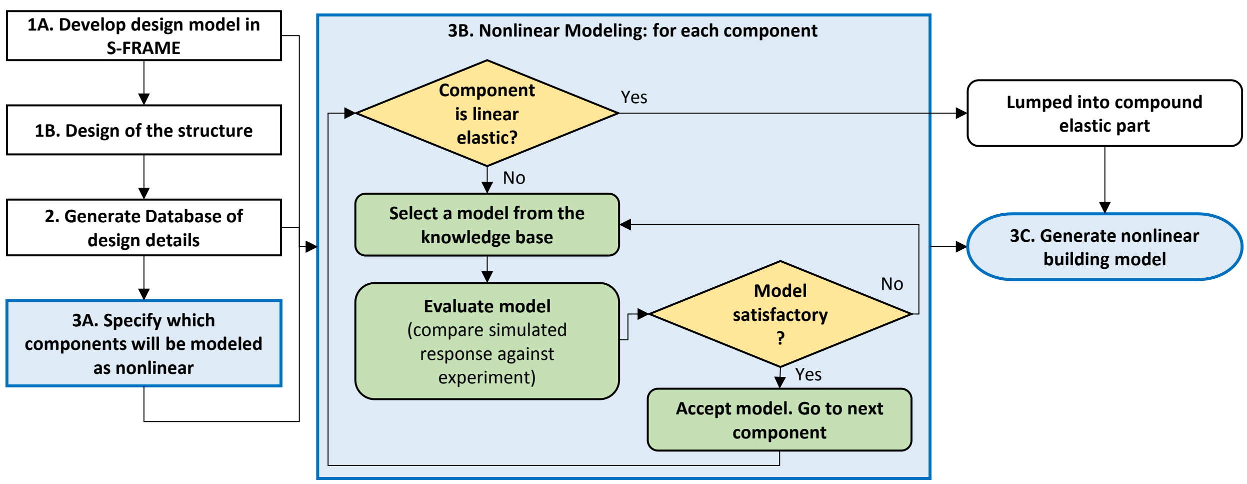


Figure 3-1. Nonlinear modeling process within the proposed framework.

After the model is built by assembling the compound elastic part and the nonlinear elements (termed *combined* model), it is ready to be run under nonlinear static or dynamic analyses, according to the PBD methodology being used for the project.

3.3 Structural Behavior and Modeling Knowledge Base

The knowledge base is meant to provide information for engineers to assist them in the nonlinear modeling process. As such, it is comprised of selected nonlinear models for typical structural components, parameter calculation guidelines and selected experimental results to illustrate the behavior of the component and to provide a comparison of the simulated response. Figure 3-2 illustrates the model validation task. In the example, an RBS beam-to-column connection by Uang and Gilton [29] is used to illustrate the behavior of a steel wide flange beam component with RBS connection to a wide-flange column. In the first simulation shown, the user selected a CP model with a bilinear law and in the second simulation the IMK model was selected. In this way the user can graphically see that the model that considers cyclic deterioration can give a much realistic response.

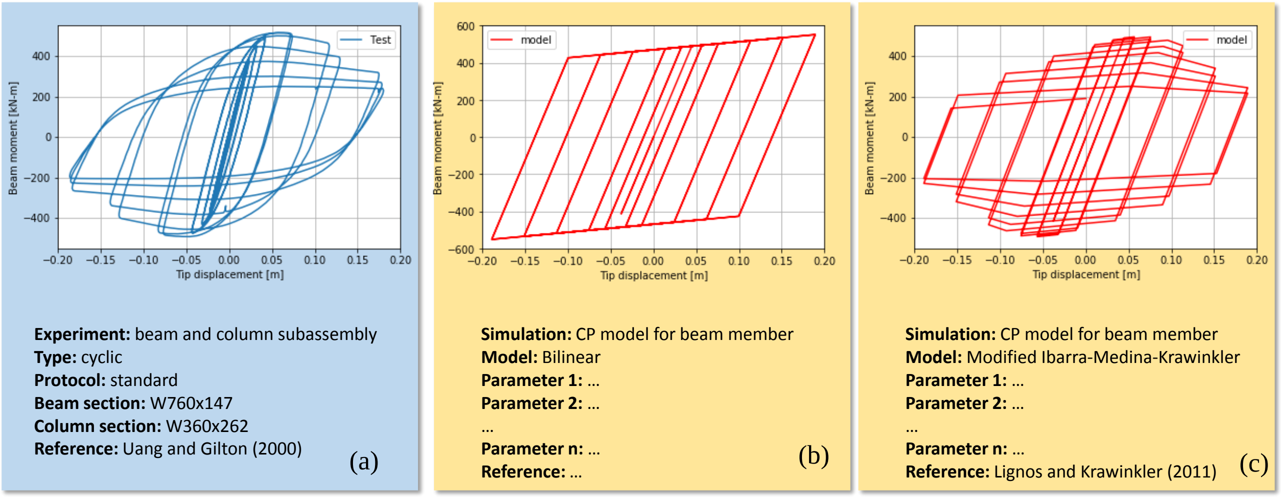


Figure 3-2. Example of an instance of model validation: (a) actual behavior, (b) and (c) simulations.

Due to lack of experimental results, it is not feasible to include a sample of an experimental test for every conceivable structural component. Therefore, the selected results are meant to cover a certain range of elements' geometry and loading history.

4 EXAMPLE APPLICATION

As an example, the framework was used to develop the tridimensional nonlinear model of a 4-story steel building, which is one of the structures used in the study by Harris and Speicher [30]. Details can be found in the report. The building has an orthogonal layout and the seismic force resisting system is at the perimeter, with two 3-bay special moment resisting frames along the E-W direction and four 1-bay special concentrically braced frames along the N-S direction, as shown in Figure 4-1(a). An elastic 3D model was developed in S-FRAME (see Figure 4-1(b)), with a level of detail typical of engineering design practice.

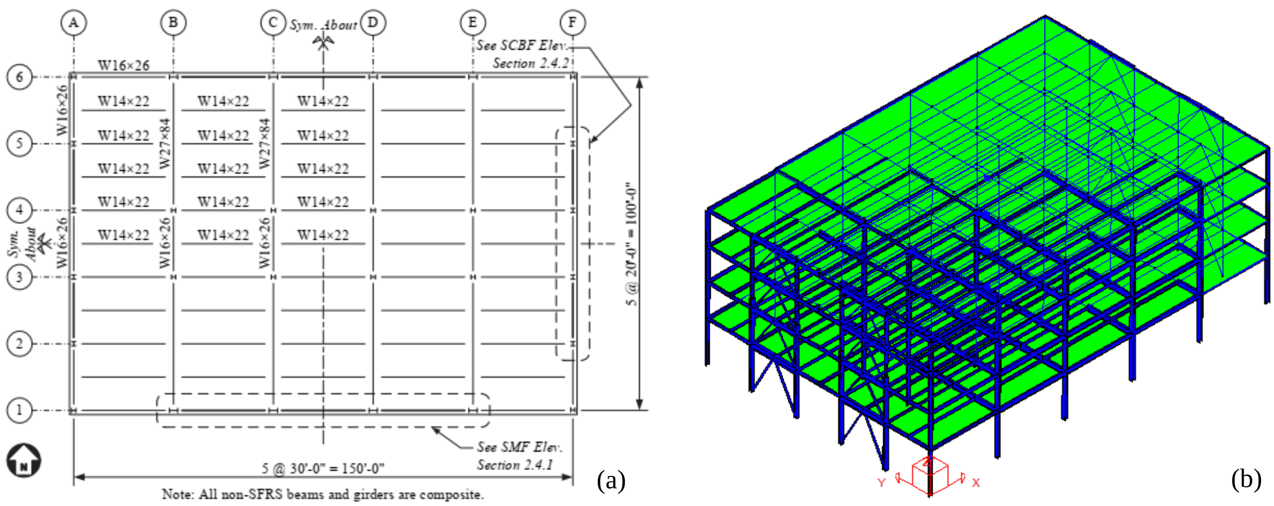
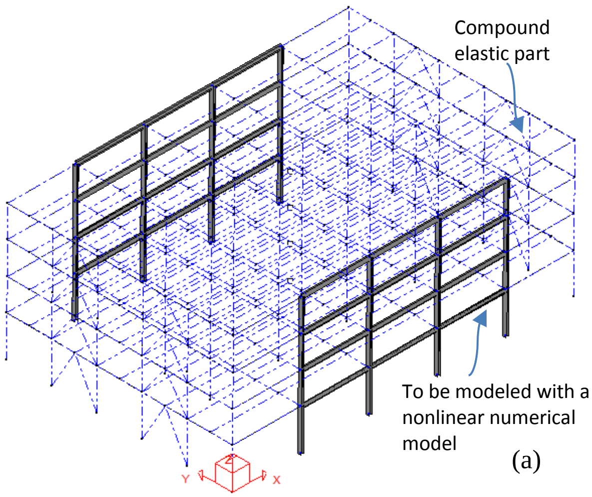


Figure 4-1. Steel building example: (a) building plan [30], (b) 3D elastic model developed in S-FRAME.

To apply the proposed framework, the structural components of the moment resisting frame system were selected to be modeled with nonlinear elements (see Figure 4-2(a)). A pushover analysis along the E-W direction is performed. For simplicity, and given the symmetry of the building, the braced frames are not treated as nonlinear components, and thus they are lumped into the compound elastic part, which is shown with dotted lines in Figure 4-2(a). A concentrated plasticity approach is used for beams and columns, with the updated backbones from [11]. Since the analysis is nonlinear static, the cyclic backbones were used to account for component deterioration. After choosing the model for each of the selected components, the expert-system takes care of the parameters of the respective nonlinear components.



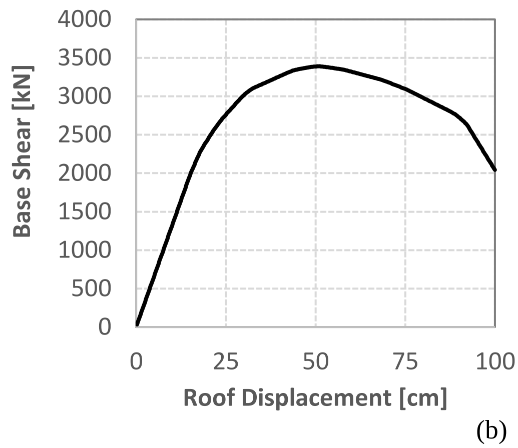


Figure 4-2. Framework application: (a) Selected structural components, (b) nonlinear static analysis result.

Nonlinear static analysis was carried out in OpenSees with the *combined* model, and the resulting pushover curve is shown in Figure 4-2(b). The results from this analysis can be used to assess the performance of the building using a nonlinear static procedure, such as the coefficient method described in ASCE 41.

5 CONCLUSIONS

In this study, a framework is proposed to bridge the gap between nonlinear modeling approaches found in research and the practical application of these models in engineering practice in performance-based seismic design of buildings. The main features of the framework are:

a. Integration of model geometry defined in the elastic design model
b. The modeling process is reduced to consultations to a knowledge base of models, thus a user can focus on important modeling decisions instead of being troubled by defining model details
c. Component models can be validated by comparing a simulated response against actual experimental behavior, and hence the modeling decision is finally made in an objective manner by the user
d. The proposed framework works with the commercial platform S-FRAME and thus it can be used for analyzing real-world structures in an efficient manner.

Research is ongoing to expand the scope of the knowledge base to include modeling of steel braced frames and reinforced concrete moment frames, among other systems, and to integrate the post-processing of nonlinear static/dynamic analysis results to the framework.

ACKNOWLEDGMENTS

The authors acknowledge the support of the Natural Sciences and Engineering Research Council of Canada (NSERC) [funding reference number CRDPJ 500576-16] and industry collaborator S-FRAME. The first author gratefully acknowledges the funding of his master studies provided by Comision Nacional de Investigacion Cientifica y Tecnologica (CONICYT/PFCHA Becas Chile Magister 2017) [fellowship number 73181195].

REFERENCES

[1] Pacific Earthquake Engineering Research Center, "Guidelines for Performance-Based Seismic Design of Tall Buildings," Pacific Earthquake Engineering Research Center, Berkeley, CA, PEER Report No. 2017/06, May 2017.
[2] F. McKenna, G. L. Fenves, and M. H. Scott, "Open System for Earthquake Engineering Simulation," 2000. [Online]. Available: http://opensees.berkeley.edu/. [Accessed: 14-Jan-2019].
[3] SEAOC, "Vision 2000 - A Framework for Performance Based Earthquake Engineering," Structural Engineers Association of California, 1995.
[4] American Society of Civil Engineers, "Minimum Design Loads and Associated Criteria for Buildings and Other Structures," American Society of Civil Engineers, Reston, VA, ASCE/SEI 7-16, Jun. 2017.
[5] Los Angeles Tall Buildings Structural Design Council, "An Alternative Procedure for Seismic Analysis and Design of Tall Buildings Located in the Los Angeles Region," Los Angeles Tall Building Structural Design Council, Jun. 2017.

[6] S-FRAME Software, Inc., *S-FRAME 3D Structural Analysis*. S-FRAME Software, Inc.
[7] Computers and Structures, Inc., "ETABS 2016 Integrated Building Design Software," Computers and Structures, Inc., User's Guide, 2016.
[8] M. Head, D. Sheri, S. Muthukumar, B. Nielson, and K. R. Mackie, "Nonlinear Analysis in Modern Earthquake Engineering Practice," *Structure Magazine*, pp. 16–20, Mar-2014.
[9] M. Head, R. Pathak, S. Muthukumar, and K. R. Mackie, "Challenging Issues When Conducting Nonlinear Seismic Analysis," *Structure Magazine*, pp. 38–40, Mar-2016.
[10] Applied Technology Council, "Modeling and Acceptance Criteria for Seismic Design and Analysis of Tall Buildings," Pacific Earthquake Engineering Research Center, 201 Redwood Shores Pkwy, Suite 240 Redwood City, California 94065, PEER-ATC-72-1, Oct. 2010.
[11] Applied Technology Council, "Recommended Modeling Parameters and Acceptance Criteria for Nonlinear Analysis in Support of Seismic Evaluation, Retrofit, and Design," National Institute of Standards and Technology, Gaithersburg, MD, NIST GCR 17-917-45, Apr. 2017.
[12] NIST, "Tech Brief 4: Nonlinear Structural Analysis For Seismic Design, A Guide for Practicing Engineers," NEHRP Consultants Joint Venture, Gaithersburg, Maryland, NIST GCR 10-917-5, Oct. 2010.
[13] R. O. Hamburger *et al.*, "ATC-114 Next-Generation Hysteretic Relationships for Performance-Based Modeling and Analysis," in *SEAOC 2016 Convention Proceedings*, Maui, Hawaii, USA, 2017, p. 13.
[14] L. F. Ibarra and H. Krawinkler, "Global Collapse of Frame Structures Under Seismic Excitations," Stanford University, Stanford, CA, John A. Blume Earthquake Engineering Center Technical Report 152, Aug. 2005.
[15] "Seismic Evaluation and Retrofit of Existing Buildings," American Society of Civil Engineers, Reston, Virginia, ASCE/SEI 7-16, 2017.
[16] Applied Technology Council, "Guidelines for Nonlinear Structural Analysis and Design of Buildings. Part IIa - Steel Moment Frames," National Institute of Standards and Technology, Gaithersburg, MD, NIST GCR 17-917-46v2, Apr. 2017.
[17] Applied Technology Council, "Guidelines for Nonlinear Structural Analysis and Design of Buildings. Part IIb - Reinforced Concrete Moment Frames," National Institute of Standards and Technology, Gaithersburg, MD, NIST GCR 17-917-46v3, Apr. 2017.
[18] Applied Technology Council, "Guidelines for Nonlinear Structural Analysis and Design of Buildings. Part I - General," National Institute of Standards and Technology, Gaithersburg, MD, NIST GCR 17-917-46v1, Apr. 2017.
[19] L. F. Ibarra, R. A. Medina, and H. Krawinkler, "Hysteretic Models That Incorporate Strength and Stiffness Deterioration," *Earthquake Engineering & Structural Dynamics*, vol. 34, no. 12, pp. 1489–1511, Oct. 2005.
[20] D. G. Lignos and H. Krawinkler, "Sidesway Collapse of Deteriorating Structural Systems Under Seismic Excitations," Stanford University, The John A. Blume Earthquake Engineering Center, John A. Blume Earthquake Engineering Center Technical Report 177, 2012.
[21] D. G. Lignos and H. Krawinkler, "Deterioration Modeling of Steel Components in Support of Collapse Prediction of Steel Moment Frames under Earthquake Loading," *Journal of Structural Engineering*, vol. 137, no. 11, pp. 1291–1302, Nov. 2011.
[22] M. Bosco and L. Tirca, "Numerical Simulation of Steel I-Shaped Beams Using a Fiber-Based Damage Accumulation Model," *Journal of Constructional Steel Research*, vol. 133, pp. 241–255, Jun. 2017.
[23] F. L. A. Ribeiro, A. R. Barbosa, and L. C. Neves, "Application of Reliability-Based Robustness Assessment of Steel Moment Resisting Frame Structures under Post-Mainshock Cascading Events," *Journal of Structural Engineering*, vol. 140, no. 8, p. A4014008, Aug. 2014.
[24] A. Gupta and H. Krawinkler, "Seismic Demands for Performance Evaluation of Steel Moment Resisting Frame Structures," Stanford University, Stanford, CA, John A. Blume Earthquake Engineering Center Technical Report 132, Jun. 1999.
[25] N. K. Psyrras and A. G. Sextos, "Build-X: Expert System for Seismic Analysis and Assessment of 3D Buildings Using OpenSees," *Advances in Engineering Software*, vol. 116, pp. 23–35, Feb. 2018.
[26] H. M. Chen and W. K. Kao, "Computer-Aided Model Generation for Nonlinear Structural Analysis Using a Structural Component Model Database," *Journal of Computing in Civil Engineering*, vol. 22, no. 5, pp. 312–324, Sep. 2008.
[27] B. Simpson, F. McKenna, and M. Gardner, *NHERI-SimCenter BracedFrameModeling*. Zenodo, 2018.
[28] Python Software Foundation, "Python 3.6.6 Documentation." [Online]. Available: https://docs.python.org/release/3.6.6/. [Accessed: 11-Jan-2019].
[29] C. M. Uang, Q. S. Yu, and C. S. Gilton, "Effects of Loading History on Cyclic Performance of Steel RBS Moment Connections," presented at the 12th World Conference on Earthquake Engineering, Auckland, 2000, p. 8.
[30] J. L. Harris III and M. S. Speicher, "Assessment of First Generation Performance-Based Seismic Design Methods for New Steel Buildings, Volume 1: Special Moment Frames," National Institute of Standards and Technology, NIST TN 1863-1, Feb. 2015.