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An Integrated Platform for Validated Prediction of Collapse of Structures

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Abstract: In developing key documents such as national building codes, regional emergency response plans, and risk management strategies, it is critical to understand the causes and effects of structural collapse. This paper presents ongoing research activities to establish a robust procedure for accurate assessment of the collapse of steel frame structures. A cohesive zone method based strategy is being developed as a standardized process for validating future finite element formulations of structural collapse. In addition, a stochastic framework is being developed to identify accurate collapse limit states and critical damage measures through incremental dynamic analysis. This paper introduces the computational simulation tool and prototype structure used for the development of the stochastic framework of collapse modeling.

1. Introduction: Due to the growing attention to accurate prediction of the collapse of structures, sophisticated models have been developed and validated for static and dynamic nonlinear constitutive modeling of such structures [1]. Such models incorporate critical effects such as multi-axial yielding; interactive system, member, and local buckling; and energy-dissipating damping or fuse systems. However, accurate prediction of structural collapse with systematic incorporation of uncertainty still remains elusive, especially for structural evaluation and design of actual structures because of challenges in modeling of fracture on a scale sufficient to simulate dynamic instability [2], obtaining experimental test results that validate computational results [3]; and identifying contributions of various damage measures to collapse despite significant uncertainties in loads and the chaotic nature of the dynamic instability of the structure [4].

Despite these challenges, understanding of the causes and effects of structural collapse is now at the core of several critical areas of national need that are being addressed actively by code-writing bodies, industry organizations, owners of structures, and government agencies in the development of such key documents as national building codes, regional emergency response plans, and risk management strategies for large-scale property owners such as hospital campuses, universities, and military installations.

The NSF-funded research seeks to transform capabilities within the U.S. for creating effective and practical computational formulations for collapse modeling by developing a new platform for validating economical collapse formulations both computationally and experimentally and for identifying systematic biases of computational formulations and contributing parameters thereof in predicting structural collapse through the use of efficient and focused stochastic algorithms.

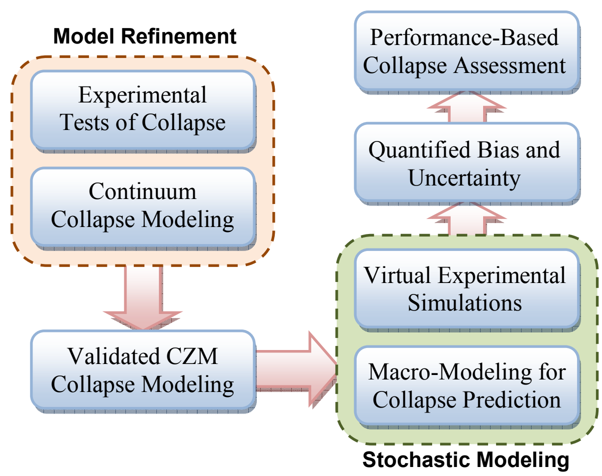


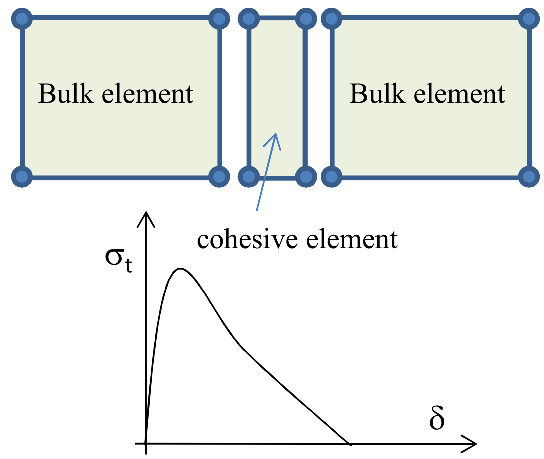
Figure 1. Integrated platform for validated prediction of collapse of structures

Figure 1 illustrates the integration between main components of the framework under development: experimental test data, computational simulations of collapse behavior using continuum and macro-models, and performance-based design and collapse assessment. First, a computational continuum modeling approach based on use of cohesive zone elements is developed to accurately predict collapse behavior and is calibrated and validated through comparison with available experimental test results. Second, using the continuum model validated by the test results, "virtual experimental simulations" are performed for a wide array of geometric, material, and loading parameters. Third, a macro-model for collapse analysis of structural systems is formulated and validated against both experiments and virtual experimental simulations. Fourth, the bias and uncertainty of macro-model predictions are quantified by developing a stochastic model of the collapse limit-state. Finally, factors correcting collapse capacity and demand are derived from the stochastic model for use in performance-based design and collapse assessment. The research aims to advance existing technologies related with state-of-the-art research so as to demonstrate the framework and to make broader and immediate impact across structural engineering research and practice constituencies.

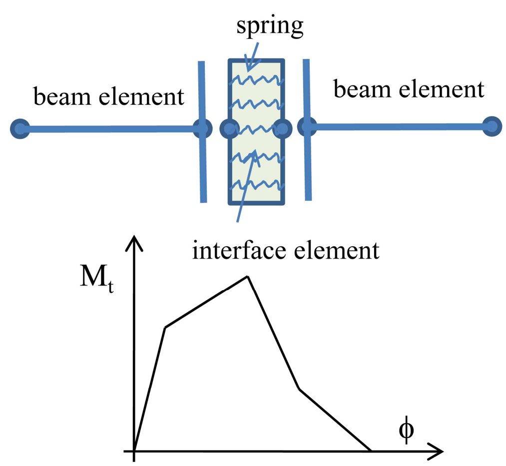
In the following sections, ongoing research activities to establish a robust procedure for accurate assessment of the collapse of steel frame structures are presented. First, we present development of a cohesive zone method based strategy as a standardized process for validating future finite element formulations of structural collapse. Second, the paper introduces the computational simulation tool and prototype structure used for the development of the aforementioned stochastic framework.

2. Development of CZM-based Macro-model for Progressive Collapse: Cohesive Zone Method (CZM) has been developed to efficiently model fracture processes in continuum mechanics (see a review in [5]). Interface elements, identified as cohesive elements and having zero width, are inserted between the interfaces of finite elements. The traction-separation relation is applied to the cohesive element along the crack path. The traction-separation properties depend on material fracture energy, fracture strength, structural response, etc. At a critical separation threshold, the complete separation of the cohesive elements occurs, as shown in Figure 2a. As the crack opening increases, more cohesive elements along the crack line are separated. Note that during this process, the number of degrees-of-freedom in the structure remains the same. The CZM is generally developed in stress-space for continuum models simulating brittle materials.

For progressive collapse, it is desirable to model the fracture process during the collapse. This study aims to develop a stress-resultant-based macro-model for progressive collapse of ductile steel structures that inherits the traction-separation properties from the CZM. "Interface elements" containing multiple springs (as shown in Figure 2b) are proposed to be inserted between beam finite elements in locations where fracture may occurs. A plasticity formulation may then be used to develop the traction-separation relation of the interface element. The deformation and separation of these springs can thus model the fracture process of the beam element. In this work, a two-surface plasticity formulation [6] will be extended to include complete fracture. This plasticity model will thus be used to model the load-deformation relationship of the "interface element." The formulation will be calibrated and validated against a range of experimental tests of steel structural components, members, connections, and systems [7,8]. Future work will extend these formulations to three-dimensional continua of ductile steel structures.



(a) Cohesive element in continuum model



(b) Interface element for beam model

Figure 2. Cohesive element and interface element

3. Nonlinear Dynamic Collapse Analysis: In order to develop a stochastic platform for validation of new macro-models, the OpenSees framework is adapted to perform nonlinear dynamic collapse analysis for several case studies. The following sections briefly describe OpenSees and provide details for a typical case study.

3.1 Simulation Tool: OpenSees — The Open System for Earthquake Engineering Simulation — is an object-oriented software framework developed by Pacific Earthquake Engineering Center (PEER) to simulate the seismic behavior of structural and geotechnical systems including the reliability computation [9]. OpenSees has been extensively employed in nonlinear earthquake engineering finite-element applications because of its advanced capabilities in constitutive models, elements and solution algorithms. Moreover, it is open-source software providing researchers with the opportunity to contribute to the framework. The authors are utilizing the OpenSees structural platform to study collapse of structures, initiating the research with a stochastic study of Incremental Dynamic Analysis [10] to identify and discuss the important parameters and limit states in the collapse assessment of structures under cyclic loadings, and to develop a macro-model incorporating fracture and disengagement of members for accurate structural collapse prediction.

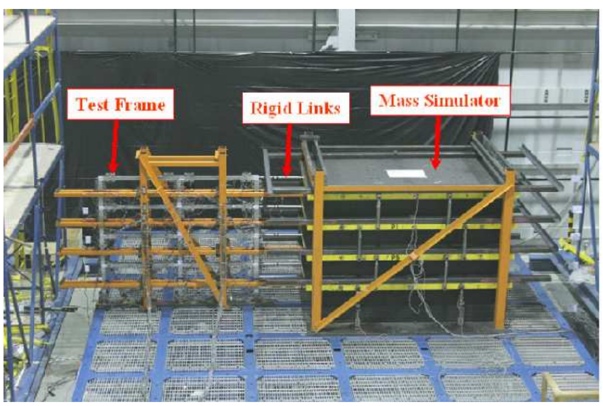


Figure 3: Shake-table test of a 1/8 scale 4-story steel frame [11]

3.2 Prototype Structure: There exist several experiments in the literature that assess dynamic performance of structures up to collapse. One of them is the shake-table test of a 4-story, 2-bay steel frame with reduced-beam sections (RBS) in 1/8 scale in [12]. Figure 3 shows the setup of the test frame, which consists of elastic members with plastic hinges at the ends, on the NEES mass simulator at the University at Buffalo. The mass simulator is connected to the test frame by means of axially rigid horizontal links through which it transfers P-Delta effects acting as a leaning column on the test frame.

In [12], rotational springs are used to analytically model the plastic hinges in the frame with a modified Ibarra-Krawinkler deterioration model [13], calibrated based on a steel component database of steel beams with RBS under cyclic loading. Moreover, panel zones are modeled at the connections considering the shear distortions. Furthermore, offsets from the panel zones are applied to take RBS into account [12].

Based on the same deterioration parameters and the mathematical model properties given in [12], an analytical model for the 4-story test frame was developed in OpenSees. The authors are ready to start performing IDA methodology by performing nonlinear dynamic collapse analysis on the built model and comparing the results to available experiment data.

4. Closing Remarks: Using the computational simulation tools described in Section 3.1, incremental dynamic analyses will be performed for the prototype structure described in Section 3.2. Using stochastic approaches such as a Bayesian parameter estimation method, critical damage measures will be identified for more accurate description of limit states and systematic treatment of uncertainties in seismic capacity, demand and model errors for collapse fragility models. These research outcomes and the computational simulation results of the CZM strategy in Section 2 will be incorporated into the integrated platform for validated prediction of collapses in Figure 1.

This research is expected to have potential impact across several structural engineering research and practice constituencies seeking to improve modeling of structural collapse as a fundamental component of the advancement of engineering knowledge. Through having these tools for validating collapse formulations and for identifying parameters necessary to characterize limit states associated with collapse, a wider range of robust formulations may be established for various levels of collapse prediction, whereas now it remains highly challenging to validate collapse of practical models needed within structural engineering. Over time, key areas of national need such as parametric studies necessary to provide information for developing building code provisions that seek to prevent disproportionate collapse; regional loss assessments that rely on accurate assessment of collapse within fragility analysis; and collapse assessment of new structural systems will all benefit from the developments in this research.

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the authors and do not necessarily reflect the views of NSF.

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