A PULL-DOWN DYNAMIC ANALYSIS OF TWO-SPAN STEEL FRAMES SUBJECTED TO PROGRESSIVE COLLAPSE

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Progressive collapse, also known as disproportionate collapse, describes a chain reaction of structural element failures in which a primary structural element failure results in the failure of adjoining structural elements. It eventually causes widespread structural damages and a disproportionate collapse. While high level finite-element models incorporating non-linear dynamic analysis will produce more realistic results in progressive collapse scenarios, they are computationally time consuming. Therefore, the development of a non-linear time history pull-down model that is validated with experimental results would be beneficial for producing acceptable and efficient design solutions, particularly for practicing structural engineers. In this paper, a non-linear time history pull-down model of a two-span steel frame is analyzed in ETABS. The ETABS model results are compared with experimental results of two steel frames with two-spans conducted by the National Institute of Standards and Technology (NIST). The NIST experiments include beam-column assemblies from the second-floor framing system of a ten-story building and each span is 20 feet long. The numerical results from ETABS pull-down analysis showed good agreement with the results from the NIST experimental study.

Keywords: Pull-down analysis, Finite element model, Time-history, Disproportionate collapse.

1 INTRODUCTION

Progressive collapse is defined as a chain reaction of structural system failure initiated from a local failure of a structural member due to terrorist attacks, gas explosions, major earthquakes, or fires. Failure in a local structural element leads to an increase in internal forces and an overload in nearby structural elements, ultimately causing a progressive collapse of the entire or a disproportionately large part of the structure. The collapses of the Alfred P. Murrah Federal Building in 1995 in Oklahoma City, the Twin Towers of the World Trade Center in 2001 in New York City, and recently the Plasco Building in 2017 in Tehran, demonstrate the disruptive nature of progressive collapse. The consequences include economic losses and casualties of human lives. Even though it is impossible to predict the timing of natural or man-made causes that can lead to progressive collapse, structures can be designed to better withstand progressive collapse.
In recent years, particularly after the events of September 11, 2001, many studies consisting of experimental programs and numerical studies have been conducted on progressive collapse of structures. Furthermore, the General Services Administration (GSA 2003) and the Department of Defense (Department of Defense 2005) have published guidelines aiming at reducing the

potential for progressive collapse when designing new or renovated buildings. Byfield *et al.* (2014), Wang *et al.* (2014) and Qian and Li (2015) have provided extensive reviews on this subject.

NIST (Sadek *et al.* 2011) generated two finite element models of structural frames in DYNA: a detailed model with a large number of elements, primarily solid and shell elements, and a reduced model with a limited number of elements, primarily beam and spring elements. DYNA accounts for both geometrical and material nonlinearities. The center stub column of the frame was pushed down under displacement control until failure occurs in both models. Moreover, an effective stress versus effective plastic strain curve was specified. For this purpose, the engineering stress-strain curve was converted to a true stress vs. plastic strain curve and several coupon tests were conducted for each steel type. Iterative finite element analyses of the tensile test were carried out, and the failure strain and the extrapolation of the true stress-strain curve were adjusted until quantitative agreement of the measured and calculated engineering stress-strain behavior in the softening region beyond the maximum stress was reached. An arrangement of spring elements was used to represent the behavior of diagonal braces in all models. The results of the numerical study were compared with the result from the experimental study and found to be in an excellent agreement (Sadek *et al.* 2011).

Kaewkulchai and Williamson (2004) created a beam-column element with multi-linearization and lumped plasticity. They studied the significance of dynamic load redistribution following the failure of one or more elements. They also created a simplified finite element model to assess the impact effect due to falling failed members on the remaining structure. Their results indicated that dynamic redistribution of loads is a significant feature of the progressive collapse problem, which should be accounted for in order to avoid estimates of capacity that are not conservative (Kaewkulchai and Williamson 2004, 2006).

While general purpose finite element software programs, such as ABAQUS, DYNA, and ANSYS are utilized for understanding progressive collapse mechanism in a research setting, structural design and capacity checks per building codes are not performed in these programs due to the expertise needed to post-process and interpret results (Lallotra and Singhal 2017). In fact, Hartmann *et al.* (2008) showed that the computations associated with the simulation of collapses of real-world structures based on conventional methods are very costly. Consequently, progressive collapse is rarely considered in conventional design limiting engineers to rely only on structural integrity considerations, such as providing standard rebar details for minimizing progressive collapse in reinforced concrete building. On the other hand, design-oriented software programs, such as ETABS and SAP2000, can handle large multi-story design projects in less time when compared to general purpose programs.

This research utilizes a design-oriented program for facilitating progressive collapse analysis for a wider structural engineering community in the design world. The model can offer engineers the capability to efficiently evaluate a wide range of column removal scenarios in new building designs. It can also aid to strengthen existing structures against progressive collapse through retrofitting techniques (Esfandiari *et al.* 2018a, Urgessa and Esfandiari 2018).

2 NIST EXPERIMENTAL TEST DESCRIPTION

One of the most important large scale studies on progressive collapse was conducted by the National Institute of Standards and Technology (NIST) (Sadek *et al.* 2011). For this experimental study, two experimental models were built: one frame designed to meet the requirements of Seismic Design Category (SDC) C with welded unreinforced flange-bolted web (WUF-B) connections, and another frame satisfying the requirements of SDC D with reduced beam section

(RBS) connections. These specimens were beam-column assemblies from the second-floor framing system derived from a ten-story building and each span measured 20 ft in length. For both the WUF-B and RBS test specimens, the beam-column assembly initially remained in the elastic range at small displacements of the center column at about 2 in (50 mm). In that early stage of the response, the behavior was shown to be dominated by flexure. With increasing the vertical displacement, yielding occurred at the beam-to-column connections, and axial tension developed in the beams, indicating catenary behavior. The axial tension in the beams increased until the connections could no longer sustain the combined bending and axial stresses, and the beam-column assemblies failed. NIST utilized these experimental results and developed computational models for determining reserve capacity and robustness of steel structures. The specification of one of the NIST test setups is shown in Figure 1.

Figure 1. Details of RBS specimen from NIST Technical Note 1669 [34].

3   NUMERICAL MODELING AND RESULTS

For this study, a nonlinear dynamic analysis method is used to compare our results with the experimental test values of NIST. First, a finite element model is built in ETABS. The default hinge properties, which corresponds to the hinge definitions in FEMA 356 (2000), were used. Then, a vertical load is applied at the place of the hydraulic ram in NIST model. While in the NIST experimental model, the specimen was unloaded and reloaded twice. However, only one-half load cycle is applied in progressive collapse. As a result, in this numerical study the maximum load is assigned to be the maximum load at the first unloading in the experimental model excluding the effects of unloading and reloading. It should be noted that having comparable results for the linear response as well as the first stage of the yielding is considered enough for design practices. A time history function is utilized to increase the vertical load until the structure collapses (i.e., vertical "pushover analysis"). Figure 2 illustrates the applied vertical load versus vertical displacements at 1/3 span of beams and center column for the RBS specimen.

Figure 3 shows the comparison of the NIST experimental test with our ETABS numerical study as far as vertical displacement profiles of beams corresponding to vertical loads for the RBS specimen are concerned. As it can be seen, there is a good agreement between numerical and experimental results. The difference can be justified by the fact that connections are not explicitly modeled in ETABS and they are considered as fixed connections. The results are close enough that can be used for future studies on progressive collapse.
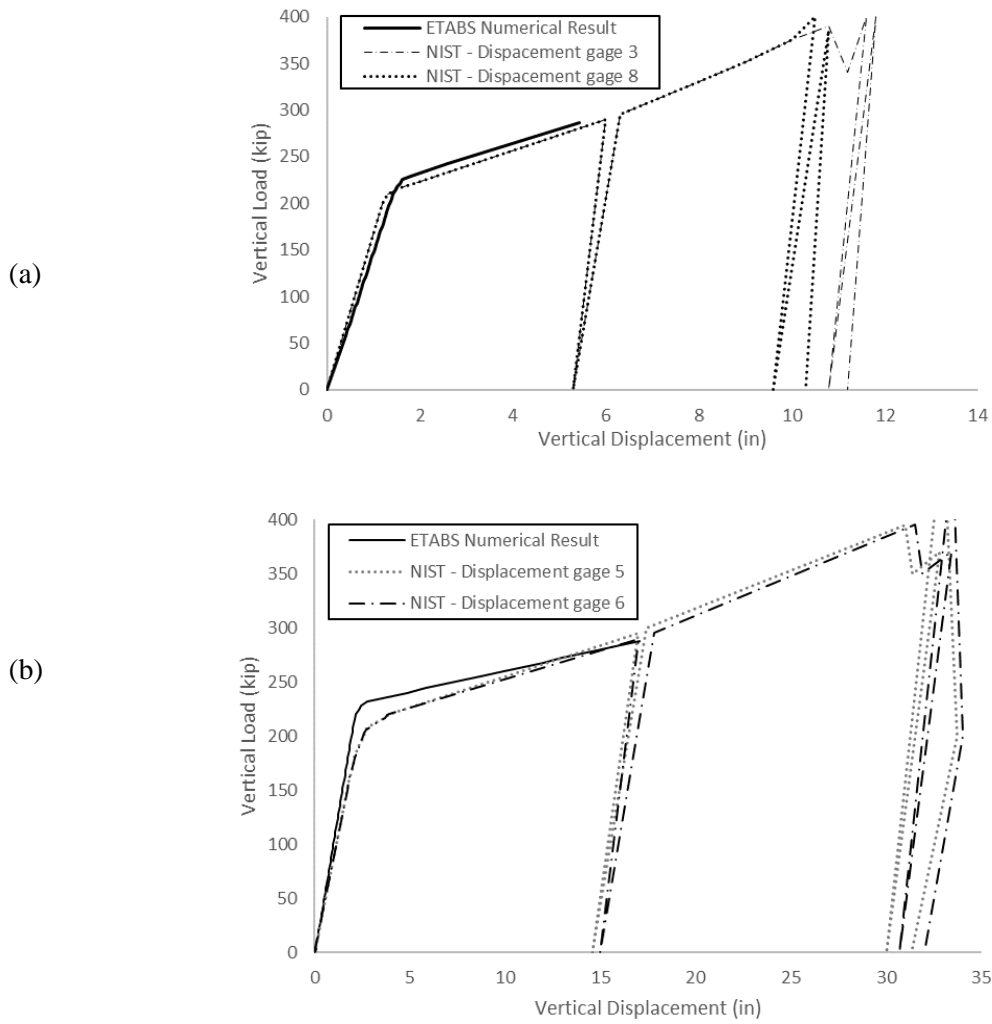
Figure 2. Applied vertical load versus vertical displacements at (a) 1/3 span of beams and (b) center column for the RBS specimen.
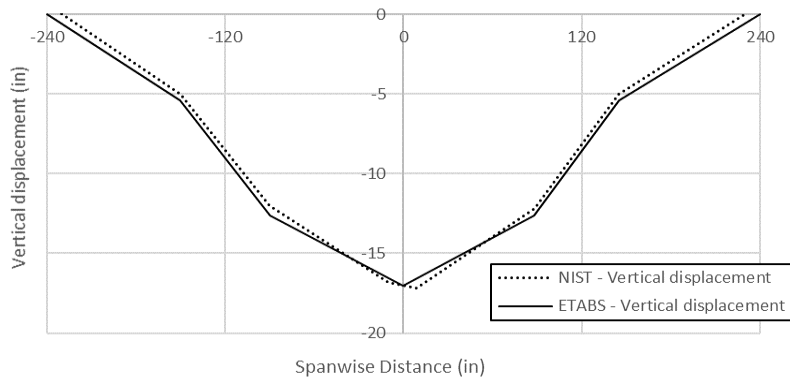

Figure 3. Vertical displacement profiles of beams corresponding to vertical loads for the RBS specimen at 286 kip.

Figures 2 and Figure 3 demonstrate that results from numerical studies using ETABS pull-down analysis are in good agreements with the NIST experimental studies.

4   CONCLUSIONS AND FUTURE RESEARCH

This paper presented a pull-down dynamic analysis of two-span steel frames subjected to progressive collapse.   The accuracy of the proposed numerical study was verified using experimental results available in the literature. While the model proposed in this article facilitates progressive collapse analysis, it can be used for addressing practical issues such as combining it with optimization algorithms for developing an integrated computational framework that is capable of incorporating robust and fast progressive collapse analysis for designing new structures or retrofitting existing structures.   The progress of our optimization algorithm is reported in (Esfandiari *et al.* 2018b, Esfandiari *et al.* 2018c, Esfandiary *et al.* 2016) and our research is underway to integrate it with progressive collapse analysis of structural frames.

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