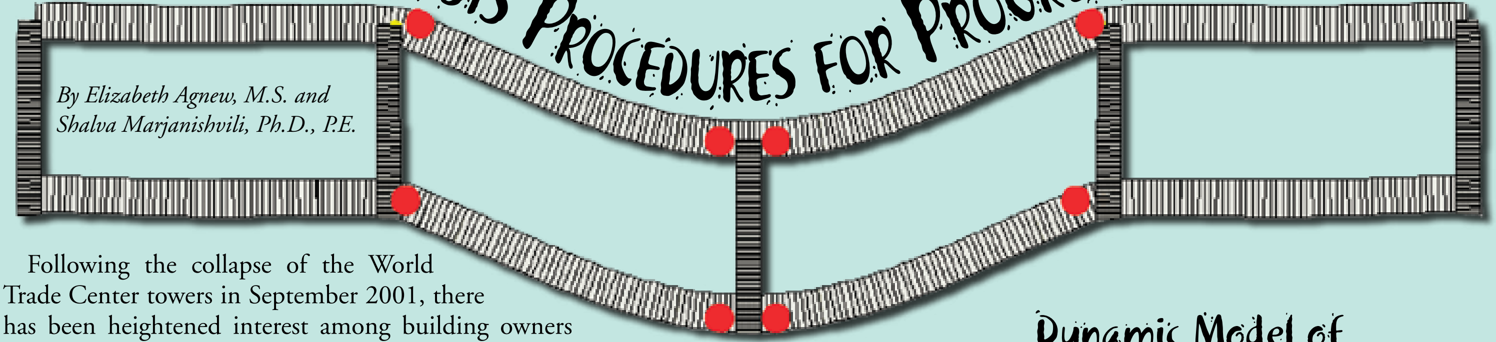
Dynamic Analysis Procedures for Progressive Collapse



By Elizabeth Agnew, M.S. and Shalva Marjanishvili, Ph.D., P.E.

Following the collapse of the World Trade Center towers in September 2001, there has been heightened interest among building owners and government entities in evaluating the progressive collapse potential of existing buildings, and in designing new buildings to resist this type of collapse. Although some technical literature addressing progressive collapse became available after the 1968 Ronan Point collapse in Britain, little research has been done in this area since the mid-1970's. Recently, the General Services Administration and Department of Defense have issued updated guidelines for evaluating a building's progressive collapse potential (GSA, 2003; DoD, 2005). However, both documents fall short of providing clear procedures for performing progressive collapse analysis using dynamic methodologies. Furthermore, both documents seem to discourage the use of nonlinear dynamic analysis procedures due to their perceived complexity.

Progressive collapse is an inherently dynamic event, and an analysis should be modeled as such when assessing a structure's vulnerability to progressive collapse. Typical static analysis procedures mandated by the General Services Administration (GSA, 2003) or Department of Defense (DoD, 2005) attempt to capture dynamic behavior through a dynamic amplification factor applied to the load (usually a factor of 2). This can be shown to be not only unconservative, but unnecessary, as dynamic analysis procedures are just as simple and straightforward to implement as static analysis.

This article demonstrates the use of commercially available finite element structural analysis software to perform dynamic analysis for progressive collapse determination using SAP 2000. The procedures presented can be implemented using any finite element program capable of nonlinear dynamic analysis.

Progressive Collapse Phenomenon

Progressive collapse occurs when the sudden loss of a critical load-bearing element initiates a chain reaction of structural element failures, eventually resulting in partial or full collapse of the structure. The cause of the initiating damage to the primary load-bearing element is unimportant; the resulting sudden changes to the building's geometry and load-path are what matter. This means that the analysis is *threat independent*. Both GSA and DoD guidelines incorporate a threat independent approach to progressive collapse analysis.

Progressive collapse is a dynamic event involving vibrations of building elements and resulting in internal dynamic forces, such as inertia and damping, whose energy may or may not be absorbed by the structure. Progressive collapse is also inherently a non-linear event in which structural elements are stressed beyond their elastic limit to failure.

Dynamic Model of Progressive Collapse

Progressive collapse analysis is carried out as threat independent by instantaneously removing one of several major load-bearing elements and analyzing the ability of the damaged structure to absorb the energy. Per GSA *Progressive Collapse Guidelines* (GSA, 2003), only one primary load bearing element needs to be removed at a time. A finite element model of the example structure with the assumed column loss scenario is shown below in *Figure 1*.

Assumptions

To simplify the analysis while illustrating the dynamic analysis procedure, the following assumptions are made:

1. The structure is modeled as two-dimensional.
2. Effects of large deflections are neglected.
3. Elastic-perfectly-plastic moment-rotation relationships are used
4. Equivalent structural damping of 5% is assumed throughout the analysis.
5. All beam-to-column connections are moment-resistant and are stronger than the beams, so plastic hinges will form in the body of the beam and not in the column or in the joint (strong column – weak beam principle).
6. All beams are adequately confined by shear reinforcement so that beams are not shear controlled.
7. Columns have adequate strength to resist additional load redistribution due to the loss of the primary column.

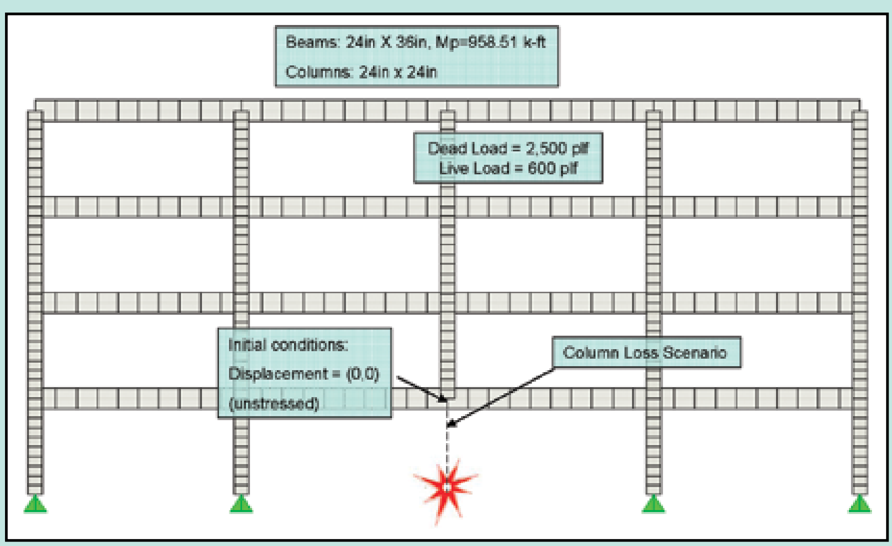


Figure 1: Finite element model of example structure

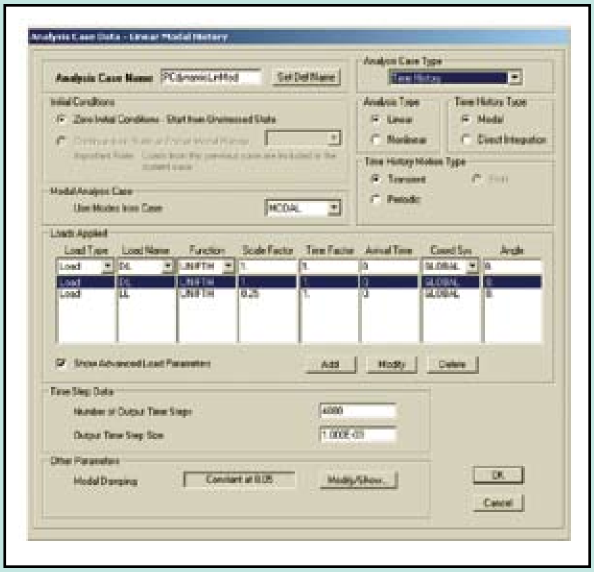


Figure 2: Analysis case data in SAP2000

Note that these simplifications are made for the purpose of this example to clearly demonstrate the usage of dynamic analysis procedure. It is up to the design professional to determine assumptions applicable for the design process.

Finite Element Model

The two-dimensional finite element model, depicting the column loss scenario is shown in *Figure 1*.

Loads

GSA Progressive Collapse Guidelines (see GSA 2003) mandates the following loading combinations when evaluating for progressive collapse:

$$Load = DL + 0.25LL \qquad \text{(Eq. 1)}$$

For the purpose of this example we have assumed the following loading conditions:

DL = 2,500 plf	uniformly distributed dead load
LL = 600 plf	uniformly distributed live load

Note that the GSA and DoD mandated load combinations differ (GSA, 2003; DoD, 2005), but the principle of dynamic analysis is the same, and so the remainder of the analysis is carried out using GSA's load combinations, outlined in *Equation 1*.

Element and Material Properties

The beams and columns are assumed to be reinforced concrete with compressive strength of 4,000 psi. Structural properties of a typical beam are listed below:

Beams:

Cross section dimensions	24 in x 36 in
Ultimate bending capacity	M_p = 958.51 k-ft

An elastic-perfectly-plastic moment-rotation relationship is assumed in the analysis.

Dynamic Analysis

Dynamic analysis for progressive collapse is carried out using an 'initial conditions' methodology (see Buscemi & Marjanishvili, 2005). This involves finding the displaced shape of the *undamaged* structure under normal loading conditions, and then applying those displacements as initial conditions to the dynamic analysis of the damaged model (i.e., the model with a column loss scenario). In other words, the column is removed from the structure, initial conditions are applied to the structure in order to return it to its undamaged shape, and then the analysis begins. This process dynamically simulates the sudden loss of the column.

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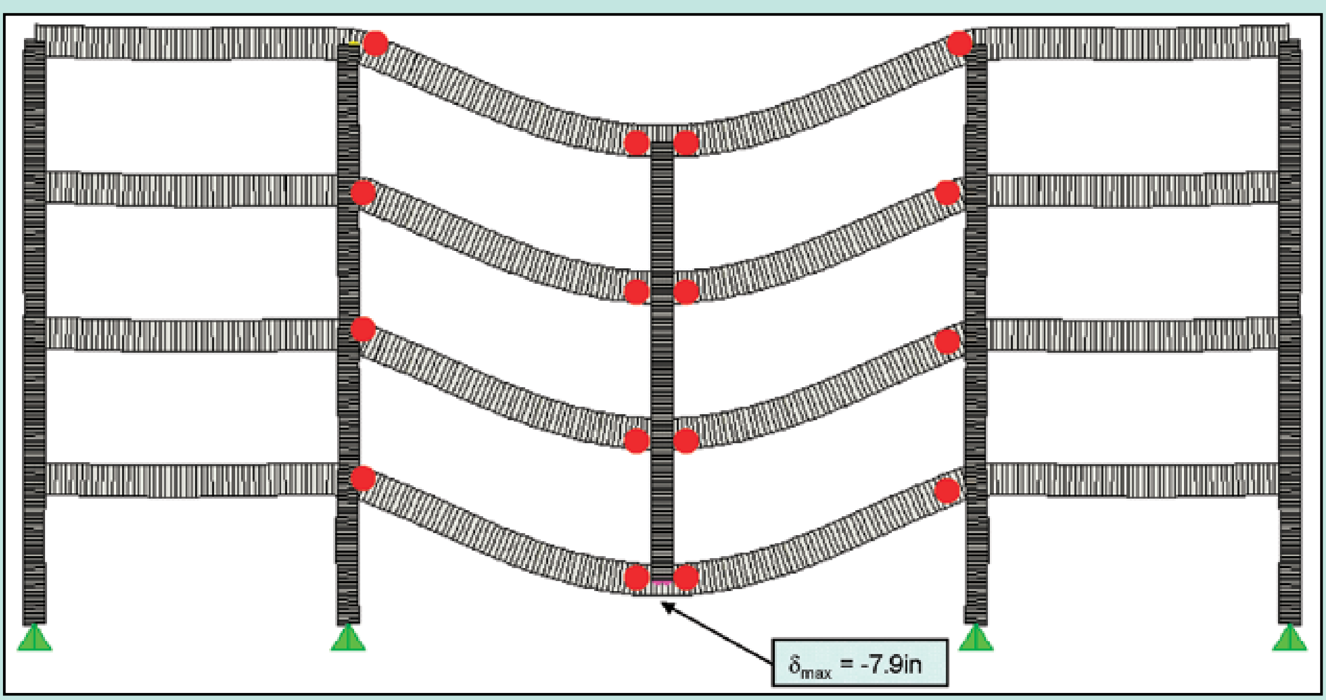

Figure 3: Plastic hinge locations

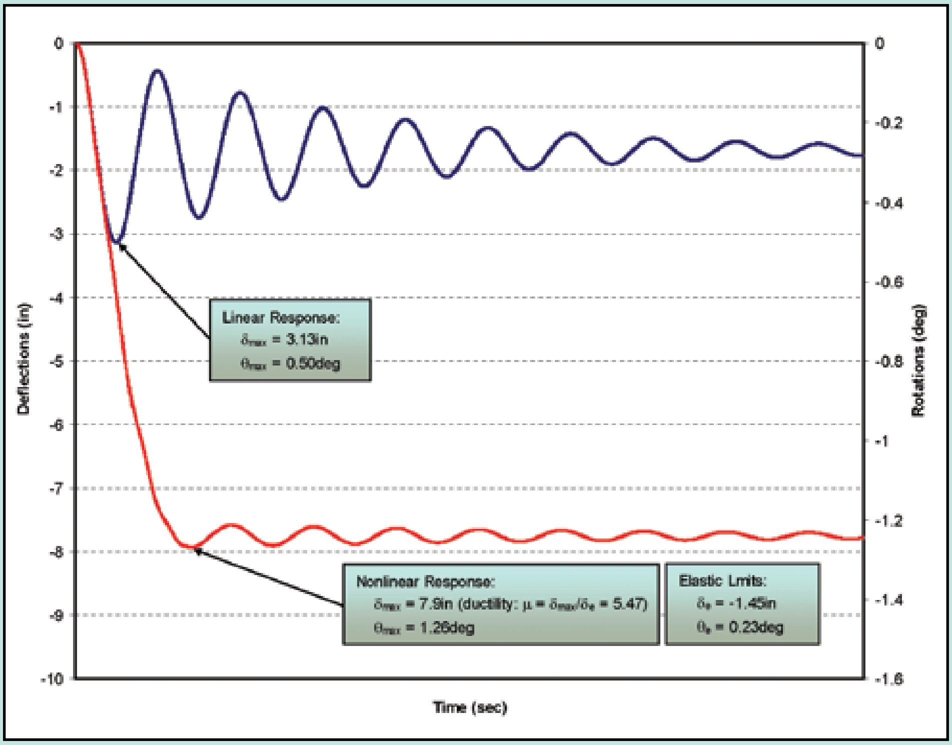

Figure 4: Dynamic analysis results

The displacements of the loaded, undamaged structure are usually negligibly small compared to the damage it will suffer after the loss of a primary column. Therefore, to simplify the analysis procedure, it is possible (and was shown by Keawkulchai and Williamson, 2003) to apply initial conditions of the unloaded, undamaged structure, i.e. "zero initial conditions". The displacements of the *unloaded undamaged* structure are the same as the displacements of the *unloaded damaged* structure — they are zero in both cases (neglecting self-weight). This allows us to model the dynamic loss of the column using the unstressed state — zero initial conditions.

Note that, if desired, the analysis can be carried out using a pre-stressed state as the initial condition. This, however, will require additional analysis steps to determine the prestressed state and corresponding deformed shape.

Linear Dynamic Analysis

The linear dynamic analysis procedure can be modeled using the initial conditions methodology and it is available in SAP2000 as one of the analysis methods. The loading input screen is shown in *Figure 2*.

After building the computer model, linear dynamic analysis involves the following steps:

1. Define the dynamic load case (*Equation 1*)
2. Perform a time history analysis with zero initial conditions
3. Analyze the time history response based on demand capacity ratio

The main advantage of this procedure is its ability to account for dynamic amplification effects. This procedure is limited to structures that are expected to remain elastic during the event.

Nonlinear Dynamic Analysis

Nonlinear dynamic analysis is performed when it is expected that structure will experience nonlinear behavior. Nonlinear dynamic analysis for progressive collapse is carried out similarly to the linear dynamic analysis procedure, with the exception that beam elements are now allowed to enter the inelastic range of deformation. This requires certain assumptions to be made for plastic hinge locations and behavior. The hinge behavior is defined above through the moment-rotation relationship, and the plastic hinge locations are defined as shown in *Figure 3*.

After building the computer model, nonlinear dynamic analysis involves the following steps:

1. Define the dynamic load case (*Equation 1*)
2. Define the plastic hinge locations
3. Perform a time history analysis with zero initial conditions
4. Analyze the results based on the maximum ductility and rotation

Nonlinear analysis is inherently more accurate than linear analysis because it accounts for the plastic behavior of the structure. The downside to this is that one must be able to predict the locations of plastic hinging in the structure, which may not be feasible for more complicated structures. Nonlinear analysis also takes much longer than linear analysis, and may involve several analysis reruns as the user varies input parameters such as step size in attempt to find a stable solution (SAP2000, 2002).

Analysis Results

Deflection and rotation time history for both the linear and non-linear analysis cases is shown in *Figure 4*.

As intended, both analyses capture the dynamic behavior involved with the sudden loss of the column. The linear static case reports a deflection of 3.13 inches, while the non-linear analysis captures some permanent displacement and maximum deflection of 7.9 inches.

Conclusions and Recommendations

1. As it is illustrated by the example presented in this paper, dynamic analysis for progressive collapse can be carried out using commercially available finite element programs, and is fairly easy to perform.
2. As is shown using SAP2000, linear dynamic analysis is as simple to perform as linear static analysis.
3. The only additional modeling for nonlinear dynamic analysis is the definition of the plastic hinging.
4. Dynamic analyses are more accurate than static analyses because they include the dynamic nature of the progressive collapse phenomenon.▪

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