

# Analytical Tools for Progressive Collapse Analysis

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## Abstract

The paper will review the tools that are available for progressive collapse vulnerability analysis and compare them in terms of capabilities and ease of use.

- What makes progressive collapse analysis different from routine structural analysis?
- What kinds of capabilities are needed in computational tools?
- Compare available tools
- Verification of predictive capabilities
- Research needs

## Introduction

Progressive collapse analyses are intended to determine the capacity of a structure either to resist an abnormal loading, thereby preserving the load carrying capacity of the critical elements, or to redistribute gravity loads of a critical load-bearing element is removed. An extensive literature search on the topic of Progressive Collapse was performed for the State Department [1] to examine how to treat progressive collapse issues for structures that do not feature hardened building construction techniques. While many of the references found in this search agreed on common features – ductility, continuity, and energy absorption – that structures should possess to help prevent Progressive Collapse, few of them offered any quantitative analytical approaches for evaluating the potential for Progressive Collapse. The scarcity of research in the field of Progressive Collapse prevention and the difficulty for most structural engineering firms to perform advanced (geometric and material nonlinear) finite element computations in an economical and timely manner has led to the development of broad guidelines that are open to many interpretations. For example, ASCE 7-98 [2] describes protection through “an arrangement of the structural elements that provides stability to the entire structural system by transferring loads from any locally damaged region to adjacent regions capable of resisting these loads without collapse.” From this approach, ASCE 7-98 discusses three design alternatives that may be part of a multi-hazard design approach. The alternatives are the indirect design approach, the alternate path direct design approach and the specific local resistance direct design approach. The Alternate Path Approach presumes a critical element is removed from the structure, due to an abnormal loading, and the structure is required to redistribute the gravity loads to the remaining undamaged structural elements. The method of Specific Local Resistance requires all critical gravity load-bearing members to be designed and detailed to be resistant to a postulated abnormal loading. Each design approach is based on assumptions and conditions that offer technical advantages and disadvantages. The merit of these approaches and the computational features that are required to perform the required analyses are presented in

the following sections. The indirect design approach does not require analytical investigation and will not be discussed here.

The response of either the elements or the structure to abnormal loading conditions is most likely to be dynamic and nonlinear, both geometrically and in the material behavior. Therefore, the analytical methods that are required to determine the response of the structure must represent the sudden application of the abnormal loading, the dynamic behavior of the materials under very high strain rates, the inelastic post-damage behavior of the materials and the geometric non-linearity resulting from large deformations. Further, the ability of the structural elements to withstand the abnormal loading or the structural system to redistribute the loads depends to a great extent on the behavior of the structural details that define the connections. As a result, the computational tools and modeling constructs that are used to analyze the damage response of structures is often critical to the success of the design approach. Perhaps most critical to the success of the design is the experience of the engineers modeling the structure and materials. The effectiveness of the analysts is further increased when the software developers are in-house and able to add features and material models that address project specific constructs.

### **Alternate Path Design Approach**

The alternate path direct design approach has the appearance of being threat independent. This approach explicitly considers the resistance to progressive collapse when a primary load-bearing member is removed. While this does not specify a threat or a cause for the damaged state, it is limited in the applicability to abnormal loading conditions that would fail only one load-bearing member. An advantage of this approach is that it promotes structural systems with ductility, continuity, and energy absorbing properties that match what the literature search found to be desirable in preventing progressive collapse. This approach would certainly discourage the use of a large transfer girder, which prevents all of the columns from extending to the ground floor. This method is also very consistent with the seismic design approach used in many building codes throughout the world. The seismic codes promote regular structures that are well tied together. They also require ductile details so that large plastic rotations can take place. This would be essential in designing structures that could resist progressive collapse when a primary load-bearing member was lost. The philosophy behind this approach is that the use of the latest computing power and advanced finite element codes allow structural engineers to reasonably bound the response of buildings to the complex phenomena of progressive collapse.

A first approximation for evaluating progressive collapse can be done using linear elastic analysis techniques. Linear elastic analyses are incapable of accounting for the redistribution of forces, P-Delta instability, nonlinear material properties including rate effects, and the development of membrane modes of resistance. Therefore, engineers using linear elastic analysis approaches use judgment, which they believe generally results in a more conservative design and then independently check for P-Delta instability after the initial design is complete. The elastic analysis, does not account for the greater capacity resulting from plastic hinge/yield line formation, membrane action or enhanced

strength due to rate dependent material properties. The advantage of this approach is found in lower cost of analysis and faster time to complete the design, however, this approach produce overly conservative designs.

Since the Alternate Path Approach is essentially an academic exercise that ignores all other damage to the structure that may accompany the removal of the critical column support, a girder spanning a single bay is instantaneously transformed into a girder spanning two bays. The transition from the original structural configuration to the damaged state is assumed to be instantaneous and therefore the structure is exposed to a dynamic effect. It is not reasonable to require a structure to respond elastically to the effects of an instantaneous column removal, therefore, structures are permitted to develop plastic hinges and sustain significant inelastic deformations when subjected to these extreme-loading conditions. This enables the structure to dissipate significant amounts of energy that would otherwise impose much greater dynamic loading to the individual members.

The effect of this dynamic phenomenon is depicted in the attached figure [1]. This figure shows the response characteristics of the standard elastic-plastic single-degree-of-freedom spring mass system typically used to represent the dynamic behavior of a structural element. The loading represented in this figure is a suddenly applied step pulse, which corresponds to the instantaneous removal of a column and corresponding transfer of the gravity load to the double-bay span. Because the transition is assumed to occur instantaneously and its duration is prolonged, the behavior to the step pulse is represented by large ratios of  $T/T_n$  (duration of loading relative to the fundamental period of the structure) along the horizontal axis.

The extent of inelastic deformation relative to its elastic limit is represented by the ductility, along the vertical axis. The greater the ductility, the more energy is dissipated in the inelastic response, however the greater will be the deformation of the structure. Reinforced concrete structures may be detailed to sustain a ductility ranging from 10 to 20 in response to an extreme loading condition.

The third scale shown next to the curves represent the required capacity (ultimate resistance) of the structural element (prior to developing the plastic hinge) as a ratio of the applied step load ( $R_u/P$ ). For a ductility of 1.0, which corresponds to an elastic response, the required capacity must be twice the applied step load in order to account for the dynamic behavior (lower most curve colored yellow). The thick black line drawn at a ductility of 2.5 (a modest amount of inelastic deformations by most accounts) is intermediate between the 1.2 and 1.3  $R_u/P$  curves. This indicates the dynamic effect of the step load of infinite duration that is suddenly applied to the inelastic structure, which requires the structure to support 1.25 times the magnitude of the step load.

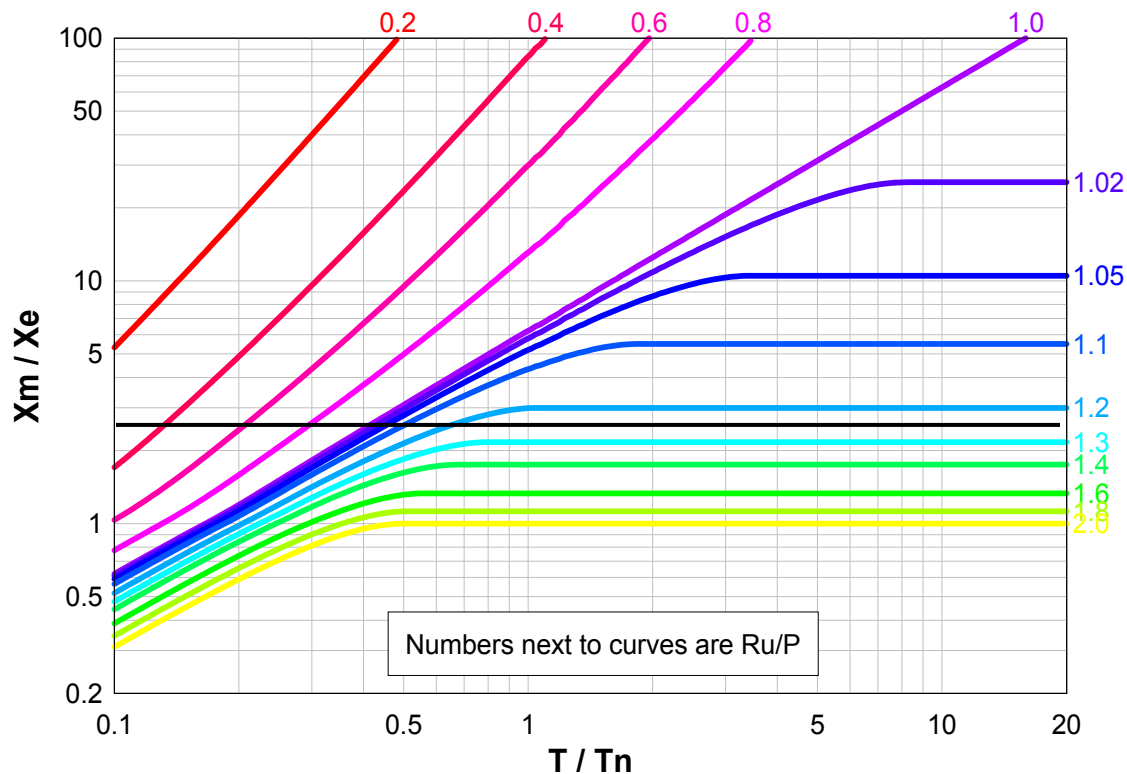


Figure 1. Maximum Deflection of Elasto-Plastic One-Degree of Freedom System for Rectangular Load.

A more refined approach for evaluating progressive collapse is through the use of inelastic finite element codes. Some representative codes include FLEX [4], ANSYS [5], ABAQUS [6], and LARSA [7]. There are also many other nonlinear finite element codes used throughout the world. These codes each have various levels of refinement that can account for the large nonlinear, time dependent results that occur when progressive collapse is initiated and when the collapse occurs. The use of these codes, in the hands of an experienced analyst, can produce the most accurate predictions of progressive collapse. However, the additional complexity comes at a larger computational expense, which can result in longer design times on the project. This time can often be justified especially in the retrofit of existing buildings where there is a large opportunity to save on construction costs.

For performing first principles computations, WAI uses the FLEX code. WAI developed the FLEX explicit, nonlinear, large deformation transient analysis finite element code for the analysis of structures subjected to air blast, fragment and ground shock loadings. FLEX has been used since 1997 in the analysis and prediction of progressive collapse for building structures. FLEX contains a library of finite elements and constitutive models that are tailored to the solution of large, transient nonlinear problems through failure. Its primary emphasis is dynamic analysis, but several static solution options are also available for combined gravitational and blast loading of buildings. Theoretically sound constitutive models for ductile and brittle materials and for pressure dependent and rate sensitive materials have been developed during the past 20 years [8-13]. These models

are available so that buildings, building components, reinforced concrete, and equipment that is constructed from metals, masonry, ceramics, and fiber reinforced composites are readily analyzed through failure. Even when using the nonlinear finite element codes, there is large room for judgment on what level of analysis will give sufficient results. Using very high fidelity models, with continuum elements and explicit solvers, can produce very accurate predictions of structural response. However, these types of models are the most computationally expensive and take the longest time to get results. For large building models, beam and shell members with nonlinear, rate dependent material models can often be combined with continuum elements to give a reasonable response with increased computational efficiency. WAI used this approach for predicting the response of explosive tests on full-scale structures. The ability to make these types of modeling tradeoffs comes from the experience of the analyst performing the calculations. The more experience with predicting actual tests and building structural models, the better chance that the results will achieve the goal of preventing progressive collapse.

### **Specific Local Resistance Design Approach**

The specific local resistance direct design approach explicitly considers resistance to progressive collapse by requiring the structure to withstand the intensity of a given abnormal loading and avert collapse altogether. This approach is often the only rational approach when retrofitting an existing building. The cost of bringing the building into compliance with the alternate path direct design method may be so great as to make the approach impractical. The specific local resistance direct design approach might allow the owner to increase the resistance of key structural elements, such as exterior columns, to resist any reasonable threat that would be levied against the structure. The specific local resistance direct design approach averts progressive collapse by hardening the vulnerable load-bearing members to a given threat using selected upgrades. These upgrades may be selective and only the most critical elements need to be retrofitted.

The specific local resistance direct design method uses the same type of computational approaches found in the alternate path direct design methods. However, since this method only focuses on key parts of the structural system at one time, the models are much smaller and more efficient to run. This reduces both the cost and project time for the design to protect against progressive collapse.

Using the FLEX code allows the use of direct dynamic blast loading on the column and the nonlinear, rate dependent material, and large deformation effects to be modeled directly. WAI conducted an investigation to evaluate the dynamic response of a set of perimeter building columns to varying intensity of blast environments. The columns were modeled with the FLEX code using end-block boundary conditions to represent the connection to the rest of the structure as shown in Figure 2. The study focused on the blast loading the existing columns could resist and the blast loading the existing columns jacketed with steel could resist. Therefore, the FLEX model allowed for the increased concrete strength due to the confining the concrete by the steel jacket. The results of the study demonstrated the ability of the jacketed columns to sustain the blast environment that would severely damage two of the unjacketed columns, thereby violating the basic

premise of the alternate path direct design method. Furthermore, the jacketed column was shown capable of sustaining a charge weight at the defensible perimeter that would damage the surrounding spandrel beams and floor slabs. This study shows one case where the specific local resistance direct design method actually improved the resistance of the existing structure to a larger threat than the alternate path method would have done.

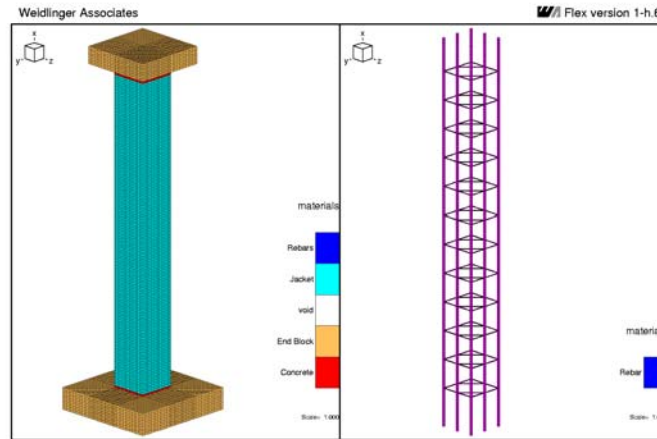


Figure 2. Specific Local Resistance Direct Design Column Model

This simplified model was compared with full building models and test data (Figure 3) so that its limits are known. Using the FLEX code still allowed the use of direct dynamic blast loading on the column and the nonlinear, rate dependent material, and large deformation effects to be modeled directly. The FLEX model also allowed for the increased concrete strength due to the jacket confining the concrete when the jacketed runs were performed. The results of the study demonstrated the ability of the jacketed columns to sustain the blast environment that would severely damage two of the unjacketed columns, thereby violating the basic premise of the alternate path direct design method. Furthermore, the jacketed column was shown capable of sustaining a charge weight at the defensible perimeter that would damage the surrounding spandrel beams and floor slabs. This study shows one case where the specific local resistance direct design method actually improved the resistance of the existing structure to a larger threat than the alternate path method would have done.



Figure 3. Column Test Response and FLEX Pretest Prediction

This study shows that in some cases the specific local resistance direct design provides more protection than an upgrade with the alternate path method. The study also demonstrated the computational advantages of the specific local resistance direct design approach using a simplified model. This can have a significant impact on the cost and viability in upgrading existing structures.

### Comparison of Available Tools

Several years ago, Weidlinger Associates examined the software and modeling techniques available in-house for analyzing global behavior of multi-story buildings exposed to abnormal loadings that damage or destroy columns or other load-bearing elements at the ground level. To reduce the study to a manageable size, three examples of increasing complexity were defined. The first two problems were 2-D and involved the removal of the center support of a two span fixed-end steel beam and a two bay multi-story reinforced concrete plane frame. The third problem was 3-D and involved the removal of either a center or corner column of a four bay by six bay, eight story reinforced concrete frame structure that accounted for the interaction between the slab, supporting beams and columns. In addition to “Biggs [14] approach” hand calculations, the different codes included commercial software STAAD, LARSA and ANSYS and in-house software FLEX. Three General Purpose codes were selected, STAAD to perform static analyses using linear material and linear geometry models, LARSA to add nonlinear geometry and ANSYS to add nonlinear material models. FLEX provided

nonlinear dynamics with nonlinear materials and geometry. Although all the software was used to solve both 2-D problems, only FLEX was used to solve the 3-D problems. The only software that satisfactorily demonstrated its ability to simulate the progressive collapse of a multistory, multi-bay frame was FLEX. The distinguishing feature that differentiates FLEX from the other software packages is the provision for nonlinear shell and beam elements to represent beams, columns, and floor systems and nonlinear spring elements to represent the local behavior of joints. Once a joint spring's maximum displacement limit has been reached, that spring is considered to 'break' and it is removed from the computational model. The spring model properties of the joint and beam connection may be backed out from detailed continuum models of the joints.

The calculated peak mid-span deflection for the simplest problem ranged from a minimum of 3.4 inches to a maximum of 4.2 inches. The shear at the supports ranged from 400 kips to 510 kips and the in-plane force ranged from 90 to 140 kips. The 2-D multistory plane frame deflections above the destroyed support ranged from 42 to 54 inches and the maximum moment at the supports ranged from 330 to 440 kip-ft. It was observed that the computed failure mode is sensitive to discretization. Softening models for post-peak behavior of the reinforcing steel makes results sensitive to mesh size in the region adjacent to the support and if no softening is assumed, the structure does not collapse.

The 3-D analyses demonstrated the capability of the FLEX software to solve progressive collapse problems. The computer time required to perform these types of analyses depend on the size of the structure and on the extent of collapse. If a structure loses the support of one of its columns, structural equilibrium might be reestablished after local failure occurs in the vicinity of the column. However, if the local failure spreads to other portions of the structure due to the overload of key structural members, this process can take a relatively long time to occur. Hence, 3-D progressive collapse problems can range in duration from 10 to 100 hours using FLEX. Furthermore, the definition of the strength properties of the beams, columns and joints from the structural drawings requires considerable experience and expertise.

Other large strain, large displacement finite element codes may be used to perform calculations similar to the FLEX analyses. The major advantage of FLEX over a similar software, DYNA-3D, involves the extensive library of material failure models, including the three-dimensional concrete model. FLEX's failure models were extensively validated against explosive test data and are available in all element types including hexes, beams and plate/shells. This allows FLEX models to contain refined 3-D models of structural details, where required, and be more coarse with beam and shell elements where warranted to reduce computational requirements. This also allows FLEX modelers to calibrate 3-D results to structural element results for simplification after the effects are understood. Additional research is required to determine the minimum modeling requirements for the large strain large displacement dynamic finite element response analyses in order to reduce the required computational resources and to analyze complex structures in a reasonable time frame.

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