

DEVELOPMENT OF PROGRESSIVE COLLAPSE ANALYSIS PROCEDURE AND CONDITION ASSESSMENT FOR STRUCTURES

Professor Ted Krauthammer
*Protective Technology Center
The Pennsylvania State University*

Robert L. Hall, PhD
Stanley C. Woodson, PhD
James T. Baylot, PhD
John R. Hayes, PhD
US Army Engineer Research and Development Center

Young Sohn, PhD
Defense Threat Reduction Agency

May 2002

INTRODUCTION

Progressive collapse denotes an extensive structural failure initiated by local structural damage, or a chain reaction of failures following damage to a relatively small portion of a structure. This can be also characterized by the loss of load-carrying capacity of a relatively small portion of a structure due to an abnormal load which, in turn, triggers a cascade of failures affecting a major portion of the structure.

From an analytical viewpoint, progressive collapse occurs when a structure has its loading pattern or boundary conditions changed such that other structural elements within the structure are loaded beyond their capacity and fail. The residual structure is forced to seek alternative load paths in order to redistribute the loads applied to it. As a result, other elements may fail causing further load redistribution. This process might continue until the structure can find equilibrium either by shedding load, as a by-product of elements failing, or by finding stable alternative load paths.

Perhaps, the most dramatic example of progressive collapse occurred in 1968 when an internal gas explosion seriously damaged the Ronan Point residential apartment building in London, UK [1]. The explosion occurred on the 18th floor as a result of build up gas from a domestic cooker, and the exterior panels of the kitchen blew

outwards. The result was that the entire corner of the building above and below the location of the explosion collapsed.

Though the overall collapse of the World Trade Center Towers in New York on September 11, 2001 still requires detailed study, it is clear that the global collapse was initiated by local damage (i.e., immediate damage from the aircraft impacts, enhanced by high temperature effects due to fires) [2]. This fits very well with the definition of progressive collapse.

The most significant difference between progressive collapse and global collapse is the initiation by relatively localized damage, and an evolution time to the global collapse. These two characteristics of a localized damage initiation and a delay time (if the global collapse cannot be avoided) may enable one to control the type and range of progressive collapse to minimize the extent of final damage.

The prediction of possible progressive collapse under specific conditions may provide very important information that could be used to control or prevent progressive collapse. It is now clear that abnormal loadings must be taken into account when designing structures. Abnormal load events could arise from a number of sources: gas explosion; confined dust or vapor conflagration; machine malfunction; high explosive effects; missile impact etc. However, to date, no adequate tools exist that can perform a progressive collapse analysis with acceptable reliability. Therefore, two main analysis techniques should be developed to serve as the fundamental bases for fundamental and practical progressive collapse assessment. In the design state, it is very important to predict the behavior of possible progressive collapse, as accurately as possible, for the various abnormal loads that should be considered.

One should be able to define a desired stable state of a partially damaged or partially collapsed structure for various abnormal loads and local damage combinations. Such collapsed cases, in reference to the predicted collapse trends, and the damage evolution rate should be determined. Since the building after a partial collapse might be still exposed to a next phase of collapse, the residual capacity of a partially collapsed structure will determine its robustness, accordingly. A damaged or partially collapsed structure could be very dangerous without enough information about its expected behavior. The rapid prediction of future behavior, or the next phase of collapse, can increase the safety of both the occupants and rescue personnel.

It is acknowledged that the Government Services Administration and the Department of Defense have made great efforts to define a practical procedure to include progressive collapse considerations in the design process. The main objective in this paper is to present a procedure for studying progressive collapse both theoretically and numerically, then, to establish a reliable structural damage assessment procedure to predict a possible future phase of progressive collapse.

The anticipated theories and procedures will be verified by innovative numerical simulations and laboratory tests.

PREVIOUS RESEARCH

In the past, some structures designed to withstand normal loading conditions were able to resist abnormal loads. This was due, in part, to the inherent strength and continuity of most traditional forms of engineered construction. Recent developments in the efficient use of building materials, innovative framing systems, and refinements in analysis techniques have resulted in structures with a considerably smaller margin of safety. Such structures may have little reserve capacity to accommodate abnormal loading conditions. Although certain forms of construction are more susceptible to progressive collapse than others, it has been noted that this type of collapse can occur in almost all types of construction [3]. It is unsafe to assume that a structure designed for normal conditions can withstand abnormal or accidental load conditions.

In the field of design, the approaches for reducing the risk of progressive collapse may be categorized as follows: (1) Event control; (2) indirect design; or (3) direct design. Event control refers to avoiding or protecting against an incident that might lead to progressive collapse. Since this approach does not increase the inherent resistance of the structure to progressive collapse and is dependent on factors outside the control of the designer, its application could be very limited. Indirect design is used to develop resistance to progressive collapse by specifying a minimum level of strength, continuity, and ductility [4-5]. The provision of specified minimums (e.g., tie forces) for strength and continuity in a code is attractive for a typical structure if the requirements are sufficient to develop an alternate load path if a portion of the structure fails. However, unless the reasons for the minimums are apparent in the code, a designer of an unusual structure may either overlook or misinterpret the requirements. Minimum requirements would also have to be established for different types of construction, could often involve research work [6], and would have to be carefully updated as construction practices change. Bases for establishing these minimum criteria are mentioned under direct design, next.

Direct design considers explicitly during the design process a structure's resistance to progressive collapse and its ability to absorb damages. The two basic means of direct design are the specific local resistance method and the alternate path method. The first method seeks to provide sufficient strength to resist an extreme loading event. This approach requires that a specific collapse-initiating event be identified so that the local resistance can be referenced to a specific limit state, which may be considered a drawback in view of the paucity of data on such events. As a consequence of developing resistance in critical elements and joints, sufficient strength and continuity may result in also providing alternate load paths. This approach is recommended primarily for situations when the loss of an element cannot be tolerated by the structure. In contrast to the specific local resistance approach, the alternate path method directs a designer's attention toward the behavior of the structure after some damage has occurred, regardless of cause, and relies on continuity and ductility to redistribute force within the structure. This is attractive because the limit state considered is directly related to the overall structural performance in the event of an accidental overload, and the collapse-initiating event need not be specifically identified.

In comparing with the evolution in design concepts, the analytical developments have not kept up. So far, there are few numerical examples of relevant computational schemes, such as the Distinct Element Method (DEM) [6] or the Discontinuous Deformation Analysis (DDA) [7], applied to demolition or seismic damage analyses [8]. The commonly used finite element codes can only be used after making complicated modifications to simulate dynamic collapse problems which contain strong nonlinearities and discontinuities, such as hinging or fractures due to flexural behavior, shear damage, or buckling. Though the examples have shown the phenomenon of progressive collapse, there are no adequate numerical procedures to track progressive collapse that include coupled and complicated failure mechanisms.

Immediately after progressive collapse is arrested, the temporary stable structural components have a different internal energy distribution. Since the unexpected and hardly predictable energy distribution combined with possible changes in loads can bring about a second phase of progressive collapse, the damage evolution rate and internal force distribution should be identified. This can be accomplished by applying a system identification technique. Many system identification techniques exist for various cases. We can examine and verify selected cases for such predictions. Most partially collapsed structures have nonlinear characteristics. Unfortunately, only a few system identification techniques exist for nonlinear behavior. Therefore, special system identification procedures have to be developed. There have been no attempts to apply system identification techniques for partially collapsed structures. Specific procedures regarding nonlinear structural states can be modified for this purpose, to correlate a structural condition and measurable parameters.

As an example of the complexity [8], the US Army Engineer Research and Development Center (ERDC) has performed high-performance computing simulations to study the potential for progressive collapse of the Kobar Towers structure. The effort involved simulations of alternate scenarios for the Khobar Towers event. The ERDC was asked to determine the damage that would have been incurred by the Khobar Towers building if the charge had been placed in an alternate location. The Khobar Towers was constructed primarily of pre-cast wall and floor panels that were attached together during the construction process. Details of the connections are extremely important to the accurate prediction of initial damage and potential progressive collapse. A very quick turn around time was required for this analyses and simplifying assumptions had to be made to accomplish the analyses. The entire Khobar Towers structure was modeled using shell elements. The components of the structure were tied together using tie-breaking elements designed to represent the strength of the connections used in the building. Previously determined loads were applied to the sides of the structure closest to the detonation location. The analyses were performed using the explicit dynamic finite element code, DYNA3D [9]. Because of the potential for progressive collapse, gravity loads were turned on at the beginning of the analysis.

The analyses demonstrated that significant damage to the structure would be incurred. All of the loaded walls of the structure would be blown in and the floor slabs supported by those walls would eventually start to fall. Failure of interior walls was caused by impact of debris from exterior walls. Many of the connections between walls and floors

failed due to shock transmitted through the structure. It was clear that some components of the structure were going to fail due to removal of supports, but the analyses could not be carried out long enough to capture these effects due to the excessive distortions caused in the directly loaded elements. This structure was an example of a global failure due to overload of the entire structural system. The analysis points out some of the requirements for predicting damage and potential progressive collapse. The initial response of the structure can be predicted using explicit finite element analyses. This does a good job of starting the analysis, but is not, in general appropriate for continuing the analysis to complete determination of the final state of the structure. Once the initial structure damage is incurred and the structure motion is started, the analysis should be transitioned to an implicit formulation. Severely distorted structural elements may need to be deleted so that the analysis can continue. Some care must be taken in deleting these extremely distorted elements since these elements can be a load source for other portions of the building and should not be ignored. The discrete particle method being developed at ERDC may be a means of overcoming this limitation. Instead of deleting the distorted elements, the damaged concrete becomes discrete particles. These particles will not slow the analyses, but can still transfer the loads (either impact or dead) to other structural members. The analysis would need to remain explicit until after all impacts have occurred. It is possible that a code that allows portions of the structure to be analyzed explicitly while others are being analyzed implicitly may be needed.

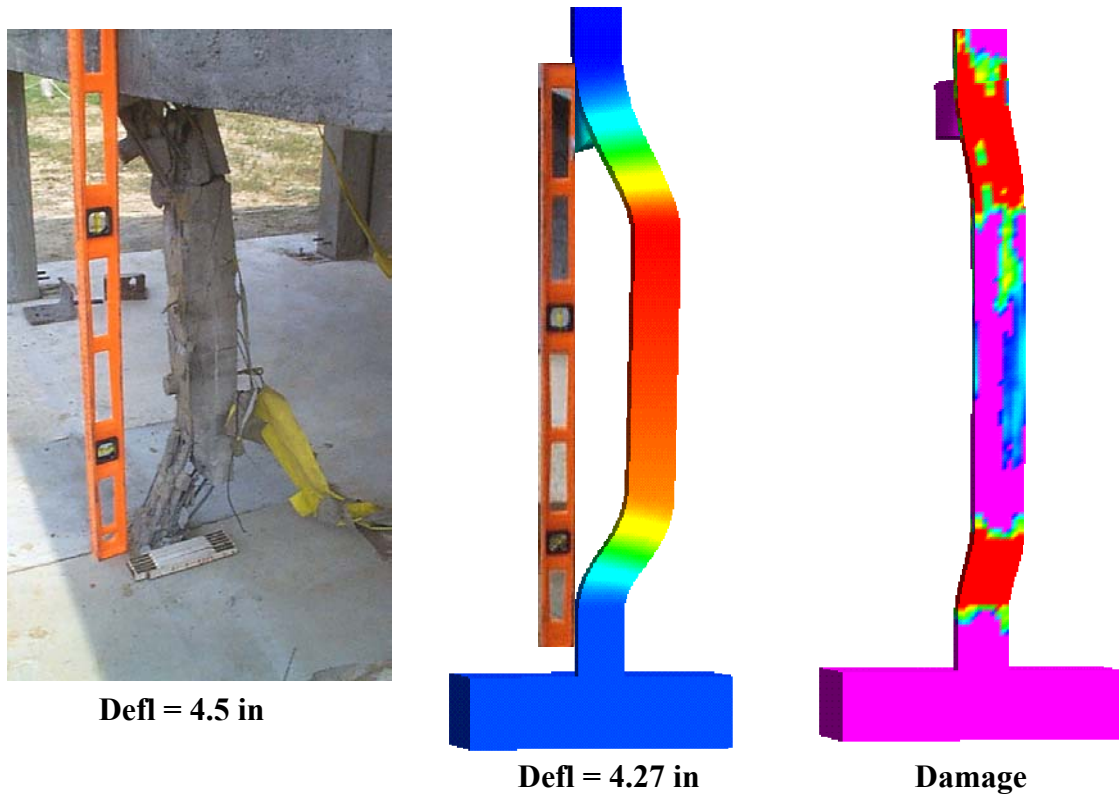
An additional study of structural collapse [10] demonstrated that the prediction of progressive collapse is not a trivial task. Experiments conducted on 1/4-scale building models, Figures 1 and 2, showed that typical slab edge beams can bridge across one destroyed column and prevent progressive collapse. Finite Element analyses using a Lagrangian large-deformation code, explicit-dynamic finite-element computer code predicted the column response well, as indicated in Figure 3. The remainder of the structure could have been modeled and the progressive collapse (or lack of it) could have been predicted in the numerical analysis.



Figure 1. Pre-test view of dynamic structural collapse experiment



Figure 2. Post-test view of dynamic structural collapse experiment



Defl = 4.5 in

Defl = 4.27 in

Damage

Figure 3. Comparison of experimental and predicted column response.

RESEARCH STRATEGY

Phase I – Progressive Collapse Analysis Methodology

The objective of this phase is to develop progressive collapse theories and to establish the corresponding analysis procedures. This phase is a critical part of the study, and it could be accomplished, as shown below:

1. **Identify Problems:** Find the characteristics of progressive collapse to be studied and determine the approach to analyze progressive collapse. The necessary theoretical basis will be established by a comprehensive literature review.
2. **Theory Review and Procedure Definition:** Clarify or modify the identified theories to analyze progressive collapse, including; geometrical and material nonlinearities, stress stiffening, stiffness variation theories etc. This procedure includes the selection of criteria (e.g. stress, strain, buckling, etc.) that might be applied to progressive collapse analysis. Also, address the expected uncertainties in progressive collapse (e.g. debris load, transient loads, damage, etc.) that might be modeled in closed form. The possible mathematical and numerical procedures should be proposed in this part of the study.
3. **Numerical Approaches and Computer Code Review:** Review and assess the analytical capabilities of commercial computer codes for their suitability to apply reviewed and selected theories for simple and advanced structural models. This assessment will enable one to define the items that should be selected and/or modified in such analyses, and how to apply them, and, also, for progressive collapse analysis.
4. **Modify and/or Develop Numerical Code:** Necessary modifications of commercial computer codes that will be developed, examined, and implemented. Development of new numerical procedures will be carried out if required.
5. **Validation:** The modified or developed computer codes will be verified and validated with simple structural models and by hand calculation
6. **Parametric Study:** After the successful validation of the simple models, typical and more realistic structural models will be selected for the purpose of a coefficient verification study. This parametric study can produce only the physical range of coefficients that should be assumed in progressive collapse analyses. The results will be used in Phase III of this study for the feasibility cross check of the numerical analyses and for practical applications.

Phase II – System Identification

This phase of the study is aimed at establishing relationships between the characteristics of progressive collapse and measurable parameters that could be used to predict the evolution in structural behavior toward possible progressive collapse.

The following steps are proposed;

1. **Identify Behavioral Characteristics:** Identify the behavioral characteristics of partially collapsed structures and their trends, and define system identification techniques that might be applicable for describing them. Determine the corresponding level of damage based on information from the parametric study results in Phase I.
2. **Theory Review and Procedure Definition:** Establish theoretical procedures and its relationship to the defined level of damage. Expand effective linear system identification theories to the nonlinear domain. Correlate measurable structural responses to the state of damage. Select effective measurable responses that can represent structural damage, including internal force distribution. Derive the relationships between selected physical behaviors and the condition of a structure.
3. **Review Computer Codes:** Since there is no single computer code that can be used to correlate measured structural behavior with structural characteristics, such a capability must be developed. One needs to assess capabilities to combine existing or new signal processing, structural analysis and system identification.
4. **Develop or Modify Numerical Codes:** The combined use of existing, modified and developed computer codes should be implemented to evaluate the structural state and the possibility of secondary/progressive collapse. The balance between calculation speed and accuracy should be determined in developing the approach for using these codes. Various approaches might be attempted before selecting the most effective procedure.
5. **Validation:** The combined approach will be verified and validated with simple models. In the application of the combined composed system identification program, carefully selected hypothetical structures will be partially collapsed to assess real application. Respectively, in the code validation, the simulated structural responses for the partially collapsed structure will be used as input data. Ambient loads will be generated and applied to the damaged structure. The analytical models of the partially collapsed structure can be obtained from the progressive collapse analysis of Phase I. The estimated structural parameters calculated from the measured data can be compared directly with the model parameters of the partially collapsed structure.

6. Parametric Study: System identification techniques that include measured data must be examined with respect to their sensitivity to noise. Such sensitivity for various kinds of noise, magnitudes and frequency contents, will be examined. For practical application, the most sensitive ranges of magnitude and frequency contents will be filtered out to increase the accuracy of the results. Another parametric study regarding collapse rate will be performed, correlating possible collapse rates directly with the structural characteristics to derive both theoretical and empirical relationships. Such relationships are expected to be useful for quick and accurate determination of structural safety.

Phase III – Physical Tests

The theoretical/numerical approach developed in Phases I and II are expected to contain significant ambiguities and uncertainties. These must be resolved or reduced significantly by accurate test data, as follows.

1. Structural Models: It is very important to select proper scaled test models that can provide objective structural test data. The objectives for such test are the verification, validation, calibration, and assessment of the developed theoretical and numerical procedures. The selected models should be able to exhibit controlled progressive collapse as a function of loads, structural components, structural damage, etc. The selection of such models can be determined based on the outcomes from parametric studies.
2. Structural Prototypes: The scaled structural models have to include the concept of dimensionless analysis to represent gravity effects, material properties, geometries and the magnitude and frequency of loads.
3. Test: The test should be designed to represent progressive collapse and its relationships with various structural and loading characteristics. For this reason, the loading mechanisms and measurement methods should be devised very precisely to capture the progressive collapse phenomena. The design of the laboratory test will be determined based on the predicted results with adequate tolerances. Such considerations must be used for both undamaged and partially damaged structural models.
4. System Identification: As a result of Phase II, there could be several candidate techniques for system identification. Since such techniques are very sensitive to various parameters, the final selection of the procedure should be determined based on results from actual tests. However, such tests cannot be done on the stable partially collapsed structure because it may accelerate the second phase of progressive collapse. Therefore, the only load that can be applied to the stable partially collapsed structure is an ambient load. The applicability of the selected system identification techniques can be examined through random processing, accordingly.

5. Test Data Analysis: The test data analysis should be separated into the following two groups: The first, for progressive collapse and structural behavior. The second, for system identification and behavior prediction. The first type of analysis should include modification of structural analysis procedures, selection of proper structural coefficients and improvements of structural modeling to simulate progressive collapse. This will enable one to analyze the prediction of progressive collapse more accurately.

The second type of analysis should include the applicability of system identification techniques by signal processing of test data for ambient loads, as well as the applied procedure itself. The analysis of test data should consider practical aspects of the procedures to increase the accuracy of progressive collapse analysis and damage assessment of partially collapsed structures.

EXPECTED RESULTS

In the design stage, the expected approach will enable one to prevent global collapse caused by localized damage that might be induced by abnormal loads. The internal force resistance mechanisms of partially collapsed structures will be estimated more accurately based on the developed approach. This outcome will also enable one to treat an actual damaged structure, and support safe and effective rescue, recovery, and evacuation activities. The resulting structural protection concept against various abnormal loads will be incorporated in general design concepts, and provide an innovative comprehensive and safe design and assessment procedure.

CONCLUDING REMARK

The main objectives of the proposed research are the development of progressive collapse analysis and damage assessment methodology of partially collapsed structures. The purpose of these developments is to enhance the safety of people in structures subjected to abnormal loads. The developed analytical methods will enable engineers to predict the type and range of possible progressive collapse in both the design stage and after incidents. This is the main reason to connect a progressive collapse analysis with a system identification procedure. This combined approach will be effective to prevent or minimize casualties and damage caused by the abnormal loads.

REFERENCES

1. Gifford, F. W., "U.K. Experience with Industrialized Concrete Construction", American Society of Mechanical Engineers, 1975, SP-48, p 35-66.
2. Bazant, Z. P. and Zhou, Y., "Why Did the World Trade Center Collapse? – Simple Analysis", Journal of Mechanics, ASCE in press, posted since Sep. 14 at <http://www.civil.northwestern.edu>.

3. Taylor, D. A., "Progressive Collapse," *Canadian Journal of Civil Engineering*, Vol. 2, No. 4, Dec. 1975.
4. ANSI "Building Code Requirements for Minimum Design Loads in Buildings and Other Structures," A58.1-81, American National Standards Institute, Inc., New York, N.Y., 1981.
5. AISC, Specification for the Design, Fabrication and Erection of Structural Steel for Buildings, American Institute of Steel Construction, Chicago, III., Nov., 1978.
6. Cundall, P. A. "A computer model for simulating progressive, large scale movement in blocky rock system," *Proceedings of the International Symposium on Rock Mechanics 1971*; II-8, pp.129-36.
7. Shi, G. H., Goodman R. E., "Discontinuous deformation analysis," *Proceedings of 25th U.S. Symposium on Rock Mechanics 1984*, pp.269-77.
8. Itoh, M., Yoshida N., Utagawa N., Kondo I., "Simulation of blast demolition of reinforced concrete buildings," *Proceedings of the Third World Congress on Computational Mechanics 1994*, pp.152-53.
9. Baylot, J.T. 1997 (Nov.) "Numerical Simulation of Alternate Scenario for Khobar Towers," Proceedings of 68th Shock and Vibration Symposium (Limited Distribution), held November 3-7, 1997, Hunt Valley MD.
10. Whirley, R.G., and Engelmann, B.E., 1993, "DYNA3D- A Nonlinear, Explicit, Three-Dimensional Finite Element Code for Solid and Structural Mechanics- User's Manual, UCRL-MA-107254 Rev. 1.
11. Woodson, S.C. and Baylot, J.T., "Structural Collapse: Quarter-Scale Experiments," Technical Report SL-99-8, US Army Engineer Research and Development Center, Vicksburg, Mississippi, 1999.
12. Itoh, M., Yoshida N., Utagawa N., Kondo I., "Simulation of blast demolition of reinforced concrete buildings," *Proceedings of the Third World Congress on Computational Mechanics 1994*, pp.152-53.
13. Ellingwood B., Leyendecker E. V., "Approaches for Design Against Progressive Collapse", *Journal of the Structural Division, Proceedings of the American Society of Civil Engineers*, Vol. 104, No. ST3, March, 1978, pp.413-423.
14. Gross, J. L., McGuire, W., "Progressive Collapse Resistant Design", *Journal of Structural Engineering*, Vol. 109, No. 1, Jan. 1983, pp.1-15.

15. Yokel F. Y., Stone W. C., "Progressive Collapse: U.S. Office Building in Moscow," *Journal of Performance of Constructed Facilities*, Vol. 3, No. 1, Feb. 1989, pp.57-75.
16. Wong, M. B., "Effects of Linearly Varying Distributed Load on the Collapse Behavior of Frames", *Computers & Structures* Vol. 61, No. 5, 1996, pp. 909-914.
17. Selna, L. G., Kim, K., "Use of Stiffness Measure in Nonlinear Response Analysis of Concrete Structures," *Computers & Structures* Vol. 66, No. 4, 1998, pp. 385-394.
18. Gupta, A., Krawinkler, H., "Dynamic P-Delta Effects for Flexible Inelastic Steel Structures," *Journal of Structural Engineering*, Vol. 126, No. 1, Jan., 2000, pp. 145-154.
19. Isobe, D., Toi, Y., "Analysis of Structurally Discontinuous Reinforced Concrete Building Frames using the ASI Technique," *Computers & Structures*, 76(2000) 471-481.