MODELING AND ANALYSIS OF PROGRESSIVE COLLAPSE POTENTIAL FOR MOMENT FRAME BUILDINGS

Sherif El-Tawil
Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, MI 48109-2125, USA

Sashi Kunnath
Department of Civil and Environmental Engineering, University of California at Davis, CA 95616, USA

Keywords: Progressive collapse; Steel Frames; Macromodel; Reduced Order Model; Nonlinear Response; Reinforced Concrete Frames; Alternate Path Method; Integrity; Robustness; Assessment; Structural Performance.

Contents

Summary

Building collapse occurs when local failure of a primary structural component leads to the failure and collapse of adjoining members, possibly promoting additional collapse. It is a dynamic process wherein the collapsing system continually seeks alternative load paths in order to survive. This chapter discusses the techniques used for modeling progressive collapse in moment resisting frame structures. Emphasis is placed on the response of non-seismically designed moment resisting steel and reinforced concrete frames since these are commonly utilized around the world. Ten-story prototype steel and reinforced concrete structures are presented and their progressive collapse resistance is evaluated using column-removal scenarios.

1. General

1.1. Scope and Objectives

Structural safety in building design is implicitly assured through reliability-based load and resistance factors. However, such provisions do not account for extreme loading events leading to progressive structural collapse. Progressive collapse of a building structure refers to the condition when the failure of a local component (or localized region) leads to global system failure. The inadequacy of alternate paths to safely transfer the loads originally resisted by the failed component(s) is one of the primary reasons that the final state of the system is not proportionate to the triggering incident. An example of progressive collapse is the loss of a single column in the lowest level of a building leading to complete collapse of the building.

This paper first discusses the various types of modeling techniques that can be used for modeling progressive collapse. Among the techniques presented, macro-models are identified as most promising for practical implementation and routine use. They are computationally efficient and at the same time they are able to adequately simulate the complex effects of large-deformation response associated with progressive collapse response of structures.

Two prototype moment resisting frame buildings (one steel and the other reinforced concrete) designed for lateral load requirements for non-seismic and seismic regions in the United States are presented. Two-dimensional models of the prototype buildings are developed using the proposed macro-models and used to demonstrate their progressive collapse resistance. The objective of the exercise is to showcase how progressive collapse analysis can be conducted using nonlinear analysis tools.

1.2. Historical Review

Progressive collapse issues first drew the attention of researchers in 1970's after the partial collapse of a panel type apartment tower at Ronan Point, England. The Ronan Point apartment block was a 22-story building constructed of pre-cast panels of two types – floor and unreinforced bearing wall. On May 16, 1968, a gas explosion occurred near one of the corners of the building on the 18th floor. The explosion blew out the non-load bearing front wall and the load bearing flank wall at the corner thus removing the support for the stories above. Lack of continuity between the structural elements and the absence of an alternate load carrying path lead to the collapse of all the corresponding floors above and below, down to the podium level. This is a classical example of progressive collapse where loss of a single load bearing members lead to a cascade of failures.

Past research on progressive collapse issues has generally proceeded in waves initiated in the aftermath of high profile failures, particularly the Ronan Point building (1968), Murrah Federal building (1995) and the World Trade Center (2001). Papers published since the Ronan disaster have documented numerous building and structural system collapses, and attempted to learn lessons from such events. These lessons can be summarized as follows: 1) increase local resistance in key regions to inhibit initiation of the collapse process; 2) impart structural redundancy in the building structural system so that it could seek alternative load paths when needed; and 3) ensure interconnection of all structural and nonstructural components to minimize debris projectiles. More recently, there have been calls to promote structural compartments to arrest collapse and limit it to small portions of a building (Magnusson 2004). In this concept, a collapse would progress horizontally until it encountered an extra strong bulkhead, or, alternatively, a weak region, where it would stop.

Mechanisms that are widely thought to contribute to the capacity of a system to resist collapse include: a) Catenary action of slab and beams allowing gravity load to span adjacent elements; b) Vierendeel action from the moment frame above a damaged column; and c) support provided by nonstructural elements such as partitions and infills. Figure 1 shows some of these effects in a frame that has lost an intermediate column.

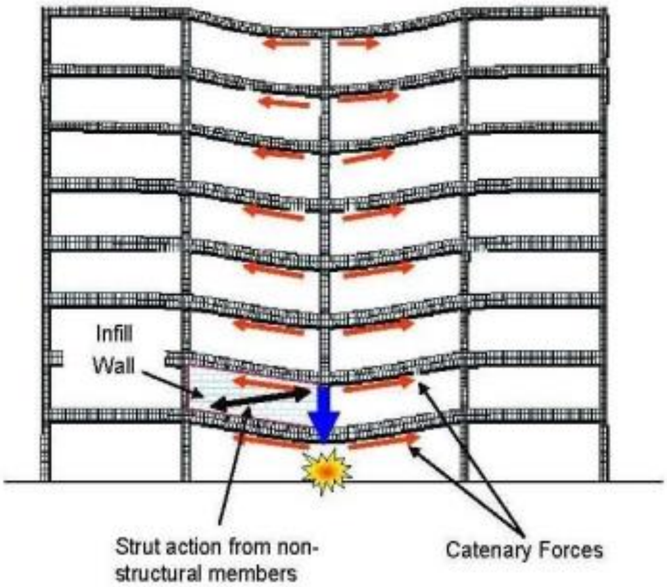

Figure 1. Collapse resistance stemming from catenary action and strut action in non-structural members

Extensive research has been conducted on progressive collapse in the past 5 years. Highlights of this rapidly growing body of literature can be found in Isobe and Tsuda (2003), who investigated collapse of frames in earthquakes, Kaewkulchai and Williamson (2004), who investigated dynamic collapse in buildings, Khandelwal and El-Tawil (2007), who investigated the collapse behavior of moment resisting steel connections and recent work by the authors and their co-workers (Khandelwal et al 2008 and Bao et al 2007) on the progressive collapse of steel and reinforced concrete moment resisting frame systems.

1.3. Current Codes and Specifications

ASCE 7-05 (2005) is the only mainstream standard in the US which addresses the issue of progressive collapse. It promotes two design alternatives to resist progressive collapse: Direct Design Method and Indirect Design Method. Both alternatives are qualitative in the sense that little implementation guidance is provided. In the former method, resistance to progressive collapse is considered directly during the design process through: (a) Alternate Path Method (APM), which seeks to provide an alternate load path after a local failure has occurred, so that local damage is arrested and major collapse is prevented, and (b) Specific Local Resistance Method (SLRM), which seeks to provide sufficient strength to resist failure at critical locations. On the other hand, the Indirect Design Method implicitly considers the resistance to progressive collapse through provisions of minimum levels of strength, continuity and ductility.

Explicit design methods for progressive collapse resistant design can be found in several US Government documents, e.g. General Services Administration (GSA 2003) - Progressive Collapse Analysis and Design Guidelines for New Federal Office Buildings and Major Modernization Projects; and Department of Defense (DoD) - Unified Facilities Criteria - Design of Buildings to Resist Progressive Collapse (UFC 2005). The GSA (2003) guidelines provide a threat independent methodology to mitigate progressive collapse potential in structures based on APM. The GSA criteria are modeled after performance-based seismic design concepts that were first proposed in FEMA-273 (1997) and allow both linear and nonlinear analysis procedures to investigate alternate load path configurations.

The UFC (2005) methodology is also a performance-based design one, and is partly based on the GSA (2003) provisions. In it, progressive collapse resistance depends on the desired level of protection (i.e. performance), which are very low, low, medium and high levels of protection. Most buildings structures fall in the first two categories and only structures that are mission critical or have unusually high risk fall in the last 2 categories. Two design approaches are specified, namely the Tie Force Method (TFM) and APM. The former is essentially an indirect design approach, wherein a minimum tie force capacity must be made available in the system to transfer loads from a damaged part to the remainder of the structure. In other words, the intent of the tie force method is to quantify minimum ductility, continuity and redundancy requirements. For a very low level of protection, it is sufficient to provide prescribed horizontal tie force capacity, while for low level of protection both horizontal and vertical tie capacity has to be provided. If adequate vertical tie capacity is not present, then APM is required. When the objective is to achieve medium or high levels of protection, structures have to be designed for prescribed horizontal and vertical tie forces, should satisfy minimum ductility requirement and should additionally be checked by APM for specific damage scenarios. In all the cases, APM is permitted only if horizontal tie capacity is present.

1.4. GSA Guidelines

The General Services Administration (GSA) Guidelines provide engineers with guidance for two potential situations: (1) reduction of the potential for progressive collapse in new buildings, and (2) assessment of the potential for progressive collapse in existing buildings. As previously discussed, the potential for progressive collapse is examined independently of any specific threat. The GSA Guidelines are limited to low- to mid-rise buildings that are 10 stories or less in height with relatively simple structural layouts. However, buildings with more than 10 stories may be analyzed using the guidelines if deemed appropriate by the project structural engineer.

Both exterior and interior scenarios must be examined for typical structural configurations. In the former scenario, a framed building is analyzed using APM separately for each of the following cases, which involve instantaneous loss of a column in the first story located:

1. near the middle of the short side of the building.
2. in the first story near the middle of the long side of the building.
3. in the first story at the corner of the building.

Buildings that have underground parking areas and/or uncontrolled ground floor areas (i.e., areas that are utilized by retail and other users, which have no operational security countermeasures in place) must be analyzed for the instantaneous loss of an interior column as well (interior scenario). Similar analyses are required for buildings with interior walls and with walls on exterior faces.

The vertical load to be applied to the structure under investigation when performing a static analysis of the building for the scenarios outlined above is recommended as:

$$Load = 2(DL + 0.25LL) \qquad (1)$$

where DL = dead load and LL = live load.

The use of 25% of the live load in Eq. (1) recognizes the fact that the probability that full live load is present during a possible progressive collapse event is small. The "2" factor is an approximate way to account for dynamic effects that amplify the response when a column or wall is instantaneously removed from a building. To evaluate collapse potential, the design material strengths may be increased by strength increase factors specified in the Guidelines.

When used in conjunction with linear elastic analysis, demand-capacity ratios (DCR) are computed for each of the structural members in the building. The definition of the DCR in is similar to that in the *NEHRP Guidelines for the Seismic Rehabilitation of Buildings* (FEMA-273 1997) and is:

$$DCR = Q_{UD} / Q_{CE} \qquad (2)$$

where:

Q_{UD} = internal force (bending moment, axial force, shear force) determined in a component or connection/joint from analyses under the vertical load given by Eq. (1).

Q_{CE} = expected strength (bending moment, axial force, shear force) of the component or connection/joint (calculated using appropriate overstrength factors, and a strength reduction factor of unity).

Failure of a structural member depends on the DCR values that are computed from the analyses described above. In typical structural configurations, structural elements and connections that have DCR values exceeding 2.0 are considered to be severely damaged or collapsed. Members with excessively high DCR values are assumed to have contributed to the collapse of the areas that they support. After the area of collapse has been established, it is compared to limiting values prescribed in the GSA Guidelines from which a decision regarding progressive collapse is then reached.

The guidelines suggest that the maximum allowable extent of collapse resulting from the instantaneous removal of an *exterior* column or wall shall be confined to the smaller of the following two areas: (1) the structural bays directly associated with the instantaneously removed column or wall, or (2) 200 m^2 at the floor level directly above the instantaneously removed column or wall. Similar limits are given for allowable collapse areas based on the removal of *interior* columns or walls, where 400 m^2 is specified in this case at the floor level directly above the instantaneously removed column or wall. Progressive collapse is assumed to occur when collapse areas that are determined from analyses are greater than the appropriate limiting values prescribed in the GSA Guidelines.

-

-

-

Bibliography

AISC-Seismic (2002), *Seismic Provisions for Structural Steel Buildings*, American Institute of Steel Construction, Chicago, Illinois. [This document contains the 2002 code requirements for seismic design of steel buildings]

Alath, S. and Kunnath, S. K. (1995). "Modeling Inelastic Shear Deformation in RC Beam-Column Joints *Engineering Mechanics: Proceedings of 10th Conference: University of Colorado at Boulder, Boulder, Colorado*, Vol. 2. ASCE, N.Y.: 822-825. [This paper presents a simple model consisting of a rotational spring to model shear distortion in RC beam-column joints]

American Institute of Steel Construction (AISC). (2006). *Steel Construction Manual*, Thirteenth Edition, Chicago. [This book contains the provisions for design of steel structures]

ANSI/ASCE 7-2005 (2005), "Minimum Design Loads for Buildings and Other Structures," American Society for Civil Engineers, New York, 2005. [This book contains the load specifications for the design of buildings and other structures]

Baldridge S.M. and Humay F.K. (2003), "Preventing progressive collapse in concrete buildings", *Concrete International*, November 2003, pp. 73-79. [This paper illustrates the inherent reserve capacity of seismically detailed reinforced concrete moment-resisting frames that make the system an excellent first step in designing to prevent progressive collapse]

Bao, Y., Kunnath. S. K., El-Tawil, S. and Lew, H.S. (2008), "Macromodel-Based Simulation of Progressive Collapse: RC Frame Structures," *Journal of Structural Engineering*, ASCE, 134(7), 1079-1091. [This paper develops a simplified approach to assess the progressive collapse resistance of RC frames under column removal scenarios]

Bazant, Z.P. and Verdure, M. (2007). "Mechanics of Progressive Collapse: Learning from World Trade Center and Building Demolitions." *Journal of Engineering Mechanics*, 133 (3), 308-319. [This paper presents an energy-based approach to analyzing the dynamics of progressive collapse of a simplified continuum building model]

Casciati, F., and Faravelli, L., (1984), "Progressive Failure for Seismic Reliability Analysis", *Engineering Structures*, Vol. 6, April, pp. 97-103. [Progressive failure of structural systems subject to seismic excitations is investigated in this paper]

Department of Defense (2005). *Design of Buildings to Resist Progressive Collapse, Unified Facilities Criteria (UFC, 4-023-03)*, USA [This document provides simple qualitative approaches to progressive-collapse-resistant design of structures]

DIANA (2009). *Finite Element Analysis*, Release 9.3, TNO Building and Construction Research, Delft, The Netherlands. [A commercial 3D general purpose finite element analysis program primarily for reinforced concrete structures]

DoD (2005) - Unified Facilities Criteria: "DoD Minimum Antiterrorism Standards for Buildings." Department of Defense, October, 2005. [This document provides the design requirements necessary to reduce the potential of progressive collapse for new and existing DoD facilities that experience localized structural damage due to extreme events]

FEMA-273 (1997), NEHRP Guidelines for the Seismic Rehabilitation of Buildings. FEMA 273/October 1997, Applied Technology Council (ATC-33 Project), Redwood City, California. [This report provides performance-based guidelines for the seismic rehabilitation of buildings]

Ferahian, R.H., (1972), "Buildings: Design for prevention of progressive collapse", Civil Engineering-ASCE, February 1972, pp. 66-69. [This paper suggests that seismic detailing of structures can enhance progressive collapse resistance]

General Service Administration (2003). Progressive Collapse Analysis and Design Guidelines for New Federal Office Buildings and Major Modernization Projects. [This document advocates the threat-independent alternative path method to assess progressive collapse resistance of buildings]

Grierson, D.E., Xu, L. and Liu, Y. (2005). "Progressive-Failure Analysis of Buildings Subjected To Abnormal Loading." *Computer-Aided Civil and Infrastructure Engineering*, 20, 155-171. [This paper proposes a quasi-static framework to study progressive collapse]

Gross, J.L., and McGuire, W. (1983). "Progressive collapse resistant design." *Journal of Structural Engineering*, ASCE, 109(1), 1-14. [In this study, the behavior of 2-D moment resisting steel frames with the loss of one of the columns or increased load on the beams representing fallen debris was examined numerically]

Gurson, A.L. (1977). "Continuum theory of ductile rupture by void nucleation and growth: Part-I Yield criteria and flow rules for porous ductile media." *Journal of Engineering Materials and Technology*, 99(1), 2-15. [Using the upper bound theorem of plasticity, this paper derives approximate yield criterion for dilatant materials]

Hallquist, J. (2005). LS-DYNA, Livermore Software Technology Corp, Livermore, Calif. [A commercial 3D general purpose finite element software platform for nonlinear dynamic analysis]

Hayes, J.R., Woodson, S.C., Pekelnicky, R.G., Poland, C., Corley, W.G. and Sozen, M. (2005). "Can Strengthening for Earthquake Improve Blast and Progressive Collapse Resistance?" *Journal of Structural Engineering*, 131 (8), 1157-1177. [As suggested by the title, this paper examines the progressive collapse resistance provided by seismic strengthening of structures]

Hinman, E., and Hammond, D. (1997). *Lessons from the Oklahoma City Bombing: Defensive Design Techniques*, ASCE, New York, N.Y. [This book describes principles and practical methods for deterring explosive threats and mitigating damage for both new and existing buildings]

International Building Code (IBC). (2003). International Code Council, Washington, D.C. [This book contains code provisions for structural design of buildings]

Kaewkulchai, G. and Williamson, E. (2004). Beam Element Formulation and Solution Procedure for Dynamic Progressive Collapse Analysis. *Computers and Structures,* Vol. 82, 639-651. [This paper present a beam-column element using lumped plasticity for collapse analysis of planar frames]

Kanno, R. (1993). "Strength, Deformation, and Seismic Resistance of Joints between Steel Beams and Reinforced Concrete Columns." Ph.D. Dissertation, Cornell University, N.Y. [This work develops methods to assess the strength and deformation characteristics of hybrid steel-concrete connections under seismic loading]

Khandelwal, K and El-Tawil, S. (2007), "Collapse Behavior of Steel Special Moment Resisting Frame Connections," Journal of Structural Engineering, ASCE, 133(5), pp. 646-655. [This paper presents the progressive collapse resistance of moment connections in special moment frames]

Khandelwal, K., El-Tawil, S., Kunnath. S. K. and Lew, H.S. (2008), "Macromodel-Based Simulation of Progressive Collapse: Steel Frame Structures," *Journal of Structural Engineering*, ASCE, 134(7), 1070-1078. [This paper develops a simplified approach to assess the progressive collapse resistance of steel moment frames under column removal scenarios]

Krawinkler, H., Bertero, V.V. and Popov, E.P. (1975). "Shear Behavior of Steel Frame Joints." *Journal of Structural Division, ASCE*, Vol.101 (ST11), 2317-2336. [This paper develops a simple model to consider panel zone deformations due to shear behavior in steel beam-column joints]

Liang, X., Shen, Q., and Ghosh, S.K. (2006). "Assessing ability of seismic structural systems to withstand progressive collapse: seismic design and progressive collapse analysis of steel frame buildings." Report, SK Ghosh and Associates, 334 E Colfax, Unit E, Palatine, IL 60067. [This report presents the design and progressive collapse evaluation of steel frame buildings]

Lowes, L.N. and Altoontash, A. (2003). "Modeling Reinforced Concrete Beam-Column Joints subjected to Cyclic Loading." *Journal of Structural Engineering*, 129(12), 1686-1697. [This paper presents a macromodel of a RC beam-column joint region for use in seismic simulations]

Magnusson J., (2004), "Learning from structures subjected to loads extremely beyond design", *Modern Steel Construction*, March 2004, pp.31-34. [This paper suggests the use of structural compartments to arrest structural collapse by limiting damage to small sections]

Marjanishvili, S. and Agnew, E. (2006). "Comparison of Various Procedures for Progressive Collapse Analysis." *Journal of Performance of Constructed Facilities*, 20 (4), 365-374 [This paper examines the effectiveness of different approaches to modeling progressive collapse behavior of structures]

Mitra, N. and Lowes, L.N. (2007). "Evaluation, Calibration and Verification of a Reinforced Concrete Beam-Column Joint Model." *Journal of Structural Engineering*, 133(1), 105-120. [This paper presents an improved macromodel of a RC beam-column joint region for use in seismic simulations]

OpenSees (2009). Open System for Earthquake Engineering Simulation. http://opensees.berkeley.edu. [This is an open-source software platform for nonlinear analysis of structures particularly seismic simulations]

Pretlove, A.J., Ramsden, M., and Atkins, A.G., (1991), "Dynamic effects in progressive failure of structures", International *Journal of Impact Engineering*, v 11, n 4, pp. 539-546. [This paper investigates progressive collapse scenarios accounting for dynamic redistribution of forces]

Shen, Q., and Ghosh, S. K. (2006). Assessing Ability of Seismic Structural Systems to Withstand Progressive Collapse: Progressive Collapse Analysis of Cast-in-place Concrete Frame Buildings. *Technical Report*, S.K. Ghosh and Associates, Inc., Skokie, IL, 2006. [This report presents the design and progressive collapse evaluation of RC moment frame buildings]

Vecchio, F.J. and Collins, M.P. (1986). "The Modified-Compression Field Theory for Reinforced-Concrete Elements Subjected to Shear." *Journal of the American Concrete Institute,* Vol. 83 (2): 219-231. [This paper develops a methodology for determining the shear stress versus strain response of RC panels]

Walraven, J. C. (1981). "Fundamental Analysis of Aggregate Interlock." J*ournal of Structural Division*, ASCE 107(ST11): 2245-2270. [This paper provides an approach to model shear transfer through a crack in reinforced concrete sections]

Biographical Sketches

Sherif El-Tawil received his PhD in Civil Engineering from Cornell University in 1996. In late 1995, he visited the Nippon Steel Corporation as a research scientist in their Steel Structure Development Center, where he developed new computational models for reinforced concrete-steel (RCS) composite connections. In Fall 1996, he joined the faculty of the Civil and Environmental Engineering Department at the University of Central Florida (UCF). At UCF, he pursued computational simulation research on steel and composite steel-concrete structures, focusing in particular on seismic hazard mitigation. In fall 2002, he joined the faculty at the University of Michigan, where he focused on how buildings and bridges behave under the extreme loading conditions generated by manmade and natural hazards such as seismic excitation, collision by heavy objects, and blast. He is currently actively investigating how to utilize new materials and technologies to create innovative structural systems that mitigate the potentially catastrophic effects of extreme loading. Much of his research is focused on the computational and theoretical aspects of structural engineering, with particular emphasis on computational simulation, finite element analysis, constitutive modeling, macro-plasticity formulations, nonlinear solution strategies and visualization techniques. He is the immediate past chair of the Composite Construction Committee of the American Society of Civil Engineers (ASCE) and the Chair of the Technical Administrative Committee on Metals of ASCE, which is the parent committee to the 9 technical ASCE committees that address metals.

Sashi Kunnath is Professor of Structural Engineering in the department of Civil & Environmental engineering at UC Davis since 2001. Prior to joining the faculty at UC Davis, he taught at the University of Central Florida from 1991-2001. He received his Bachelor of Engineering from Bangalore University, India, his Master of Engineering from the Asian Institute of Technology, Thailand and his Ph.D. from the University at Buffalo, NY. His research interests include earthquake engineering, computational methods and software development for seismic analysis of structures, damage mechanics, and analysis of structural collapse. He has authored or co-authored over 150 technical papers and has delivered invited lectures in China, Hong Kong, Italy and Japan. A Fellow of both the American Society of Civil Engineers (ASCE) and the American Concrete Institute (ACI), Prof. Kunnath was the 2001 recipient of the ACI Structural Research Award for his work on cumulative seismic damage of bridge columns, the 2008 recipient of the ASCE Raymond Reese Research Prize for work on seismic analysis of building structures and the 2009 ASCE Richard Torrens Award for his service contributions as Editor-in-Chief of the *ASCE Journal of Structural Engineering*.