DESIGNING FOR PROGRESSIVE COLLAPSE

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The progressive collapse phenomenon has been of interest to structural engineers for several decades. After the events of 9/11, the subject has gained interest from planners, officials, and the public at large. A number of well-documented tragedies, both in the US and abroad, have prompted the inclusion of special sections addressing progressive collapse issues within current design standards and codes. This article provides an overview of the topic, from the basic definition of progressive collapse, to the difficulties of understanding, analyzing and mitigating progressive collapse. In addition, some of the design standards that have been developed, and methods for designing to progressive collapse hazards are discussed. These methods range from basic design calculations to the development of software programs specializing in the analysis of progressive collapse hazards.

The structural engineering community has tried to address the subject of progressive collapse from many perspectives, in an effort to develop a universal approach to evaluating and designing for such an event. However, the inherent difficulty in developing a universal approach is that the response of each structure to specific events may be different, from the initial cause of the collapse to the way that the collapse progresses throughout the structure. This irregular behavior separates progressive collapse from other well-defined structural engineering problems such as wind, seismic, and vibration.

A number of progressive collapse cases over the course of time have attracted the attention of engineering professionals. Among these are the Ronan Point collapse, the Oklahoma City bombing of the Alfred P. Murrah building, and the collapse of the World Trade Center towers. (*Figure 1*)

On May 16, 1968, a gas explosion occurred in an apartment on the 18th floor of a 23-story precast concrete building at Ronan Point in England. The explosion resulted in a loss of support for the five stories above, and the weight of the fallen top floors caused the subsequent collapse of the floors below. At least three people were killed as a result.

On April 19, 1995, a truck loaded with explosives was parked outside the Alfred P. Murrah federal building in Oklahoma City, OK. At 9:02 am, the truck exploded, causing the collapse of a large portion of the nine-story building, as well as damage to adjacent buildings in the complex, resulting in 168 casualties.

On September 11, 2001, as part of a larger terrorist plan, two planes were flown into the World Trade Center towers. The initial impact and ensuing fires caused immense damage on several floors at the impact locations. Eventually, the structural systems of the two towers were overwhelmed by the damage they had sustained, and both buildings collapsed. A total of 2,726 people were killed as a result of these events.

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Ronan Point Collapse

Oklahoma City Bombing

World Trade Center Attacks

Figure 1

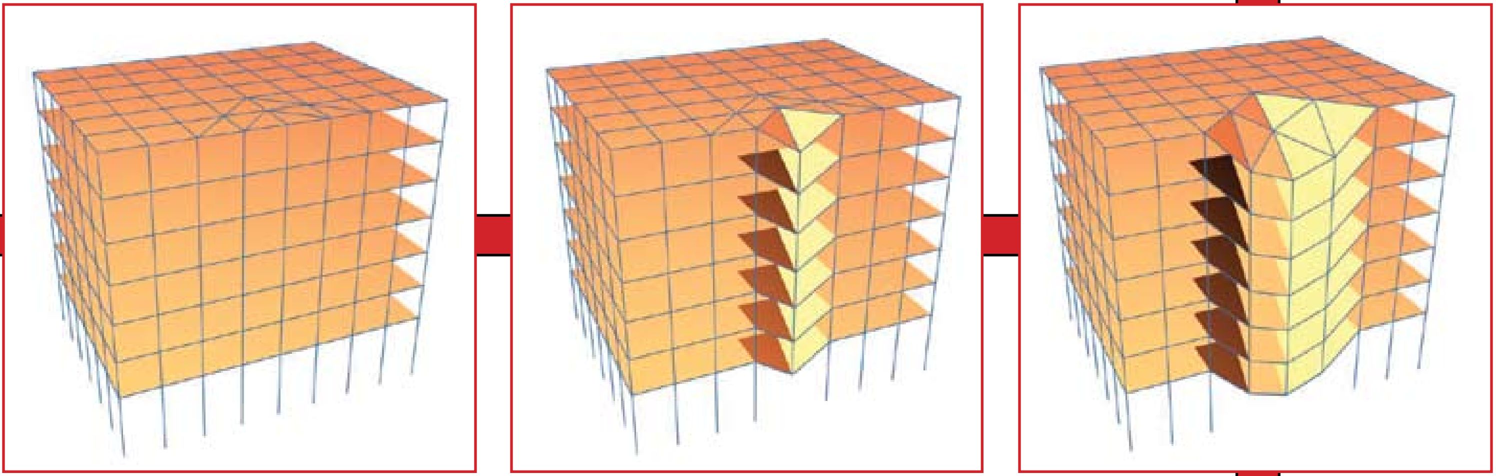

Figure 2: Phases of progressive collapse, from the intact structure (left), to initial loss of column and subsequent failures in the floors above (center), and failures propagating to other bays (right)

These three examples provide a glimpse into the aftermath of progressive collapse hazards. They demonstrate that the issue is important not only to the structural engineering community, but also to the general public. The consequences of progressive collapse can surely be quantified in dollars and cents, but more importantly, in lives lost. As such, it is necessary for engineers to develop methods for mitigating and preventing the progressive collapse of structures, allowing people to escape to safety in the event of such a disaster.

ASCE Definition of Progressive Collapse

A progressive collapse event is defined by ASCE 7-02 as "the spread of an initial local failure from element to element, eventually resulting in the collapse of the entire structure or a disproportionately large part of it."

This definition of progressive collapse provides the first indication of how to approach a progressive collapse analysis. Certainly, the first step in evaluating the progressive collapse potential in a structure is to determine whether the initial target structural element, typically a column, has failed. In some cases, the target element is assumed to fail. The next step is to determine whether this failure has spread to adjacent elements, including beams, columns, and connections. Ultimately, the engineer must determine how much of the structure is expected to fail as a result of the structural member that was lost initially. (*Figure 2*)

Evaluation Methods

Current design standards that address progressive collapse design issues include those of the General Services Administration (GSA) and the *Unified Facilities Criteria* (UFC) adopted by the Department of Defense (DoD). These standards provide two means of assessing progressive collapse in the design of new buildings or the evaluation of existing buildings.

The GSA *Progressive Collapse Analysis and Design Guidelines* have adopted a threat independent, or Alternate Path, approach to addressing progressive collapse issues. With this methodology, the designer is required to systematically remove key gravity load carrying elements (columns or load-bearing walls) around the perimeter of the building and design the remaining structure to redistribute the loads without collapse. For a regular structure, a minimum of three separate analyses is required to adequately satisfy the criteria. A ground floor perimeter column, or a portion of the ground floor load-bearing wall, must be removed at the following three locations: middle of the long side of the building, middle of the short side of the building, and a corner location. For irregular structures, such as those containing reentrant corners, soft stories, closely spaced columns, or transfer girders, additional analyses may be required to adequately address all conditions.

Figures 3a and 3b: Typical steel frame with a Vierendeel truss provides an alternative load path in the event of column failures

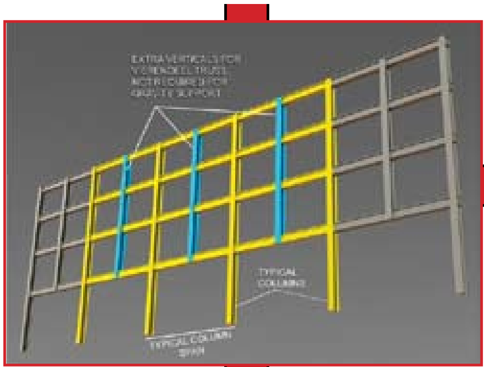

Figure 3a

In addition, the presence of an underground parking garage beneath the building would necessitate the removal of an interior column that would be vulnerable to a surreptitiously placed explosive within one of the parked vehicles. The GSA *Progressive Collapse Guidelines* permit the use of one of the following four analysis procedures: linear static analysis, non-linear static analysis, linear dynamic analysis, and non-linear dynamic analysis. The linear static analysis is the least complicated and time-consuming to perform, but could lead to overly conservative results.

The Unified Facilities Criteria document, UFC 4-023-03: *Design of Buildings to Resist Progressive Collapse*, outlines four different levels of protection, ranging from Very Low (VLLOP) to High (HLOP), and the corresponding progressive collapse design requirements. For the Very Low and Low Levels of Protection, the UFC allows for the use of tie forces in resisting progressive collapse. The tie force methodology, which is generally consistent with the design standards of the United Kingdom, is threat independent and is intended to provide a minimum level of "fault tolerance" without consideration of specific failure mechanisms. The UFC defines peripheral, internal, vertical, and horizontal tie forces that must be developed through the structural connections and sufficiently anchored at the member ends. This will effectively "tie" the structure together and allow for the redistribution of loads following local damage. The tie force methodology relies on catenary action, rather than flexural response, and therefore a structure designed in this manner will generally develop larger deformations following the loss of an element than a structure designed using the Alternate Path approach. For the Medium and High Protection Levels, an Alternate Path analysis is required, in lieu of prescribing tie forces. One of the main differences between the UFC and GSA Alternate Path methodologies is that the UFC document requires the structure to withstand the removal of any perimeter column up the height of the building (not just the ground floor perimeter columns). The UFC document also addresses the notion of Specific Local Resistance, whereby critical load-bearing elements are designed to resist a specific event without failure. Although this can be the least costly or intrusive solution, the building would still be vulnerable to collapse if the actual threat were to exceed the established design event.

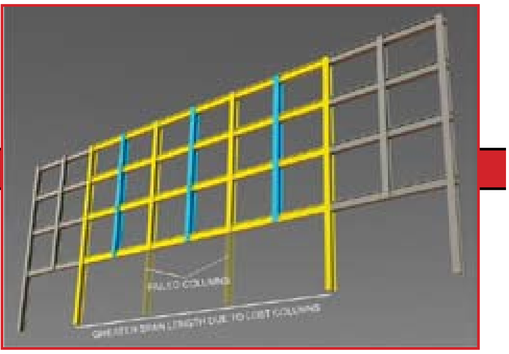

Figure 3b

Design Approaches

One of the first steps a structural engineer must take when faced with designing a system to prevent progressive collapse is to determine an alternate load path in the event of a localized failure. For example, if a perimeter column is expected to fail, the designer must find a load path to allow the load to transfer around the loss of this column without causing a large scale failure. One relatively straightforward method of accomplishing this is to simply design the beam above the lost column to have sufficient strength to span twice its original length. For example, a typical spandrel beam with a 30 foot span length would be designed to span 60 feet, assuming the loss of one perimeter column. The downside to this approach should be quite evident. As the bending moment is proportional to the square of the span length, the moment will increase exponentially. Consequently, the beams will quickly get heavy, deep and potentially quite expensive. In addition, the connections associated with these deeper beams would need to be substantially stronger, adding to the cost of this solution.

Another method of providing an alternate load path in the same situation is to provide for truss action in the frame above the lost column. If the architecture will allow for it, additional vertical elements located between the typical column bays above the ground floor can be added to the structural frame. (*Figure 3a*) This will create a Vierendeel truss in the event of a failed column. Depending on the overall height of the building, this method may allow for a relatively deep truss element and the ability to span multiple bays with little or no increase in the size of the structural members. The potential weight and member size savings using this approach has to be weighed against the need for additional vertical members and moment connections at the joints of the Viereendeel frame. *Figure 3b* provides a graphical representation of this concept, which has been used very successfully in a recently completed steel framed building for the General Services Administration (GSA).

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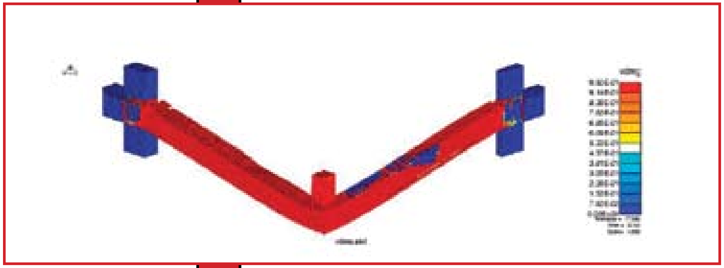


Figure 4: Example of finite element simulations used in developing ProCAT

Analytical Solutions

In designing a building to resist progressive collapse failures, the engineer must make certain assumptions on the types of loading that will induce progressive collapse. These may include the type and size of the threat, and the proximity to the building. This applies to both new designs and retrofit of structures to resist progressive collapse. However, the inherent shortcoming in this approach is that the engineer cannot accurately predict the actual event all of the time. The engineer can make educated engineering assumptions based on previous events and design guidelines such as the GSA and DoD criteria.

Ultimately, two of the primary factors in designing for progressive collapse resistance, or other types of extreme loading, are cost and practical use. For commercial buildings, or other civilian structures, it is not practical to design the buildings as military bunkers, particularly since people typically do not want to spend their daily lives in military-type structures. Besides this, designing buildings to resist every possible scenario for extreme loadings becomes prohibitively expensive and impractical. In conventional designs to resist extreme scenarios, there is typically a level of acceptable risk or damage, i.e. one bay or one floor, etc. The impact of localized damage on the stability of a structure is what warrants a comprehensive assessment.

In the event of a disaster, it is necessary to quickly assess the potential for progressive collapse failure in a structure. As Ronan Point, Oklahoma City, and September 11th demonstrated, there are many different scenarios that may initiate a progressive collapse, and while it is possible to design for extreme loading scenarios such as the loss of a column, it is not always possible to accurately predict the severity of an event. In addition, even if a building has been designed for a progressive collapse scenario, the urgency of a disaster does not allow time for engineers to search through their archives, trying to determine whether the event that occurred could be sustained by the building's design.

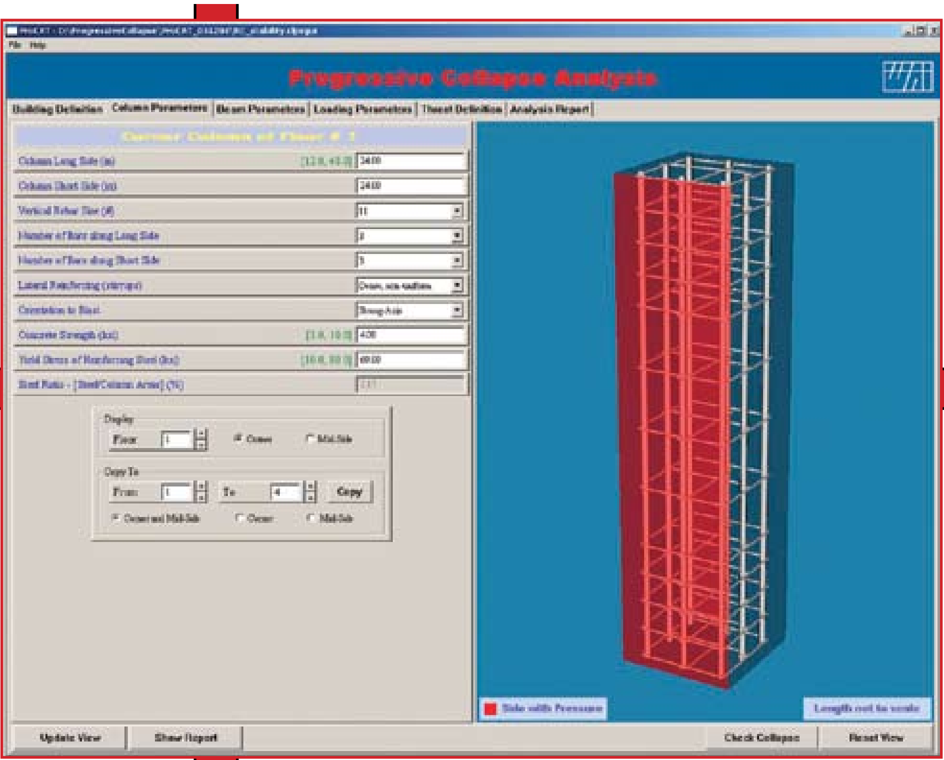


Figure 5: Reinforced concrete column data input for ProCAT. Column face highlighted in red indicates direction of blast loading.

In such cases, it is useful to have a rapid means to assess the potential for progressive collapse in a building. Such a tool has been developed by Weidlinger Associates, Inc. in the form of fast-running software compatible with all personal computer (PC) platforms. The Progressive Collapse Analysis Tool (ProCAT), was developed using numerous high-fidelity finite element simulations, parametrically varied with respect to structural design and blast environments.

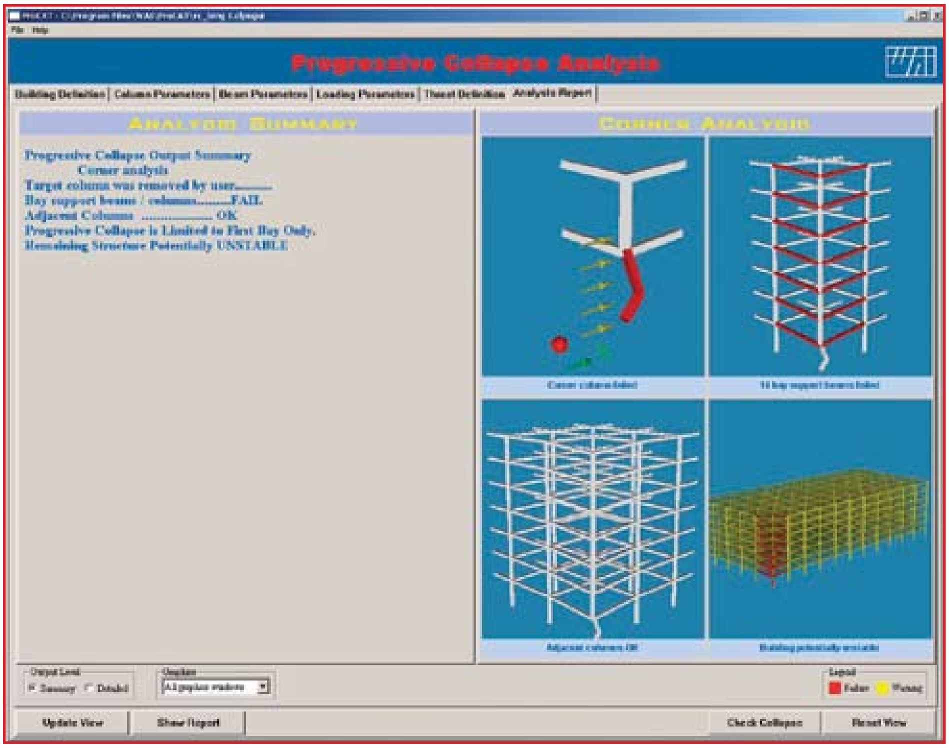
Figure 4 provides an example of the types of simulations that were performed. These simulations were encapsulated in an extensive database of response surfaces, which provide the backbone for the software.

ProCAT allows the user to evaluate a steel or reinforced concrete frame structure by defining the basic properties of the building and defining a threat scenario. The properties of the building include the column, beam, and floor slab definitions, span lengths, floor heights, total number of bays, and total number of stories. *Figure 5* shows an example of the column data input. The face of the column that is highlighted red indicates the face that will be loaded by the blast.

The analysis can be defined as either threat-dependent or threat-independent. In the threat-dependent scenario, the software will determine whether a defined threat will collapse the target structural element, typically a column, and if this will subsequently destabilize the remainder of the structure. In the threat-independent scenario, the software assumes that the target column will fail, and evaluates the response of the remaining structure. The analysis provides the user with information regarding the status of the target column, the possible failure of the surrounding bays and the floors above the target column, and the overall stability of the structure. (*Figure 6*)

ProCAT provides a simple, accurate, and efficient evaluation of progressive collapse potential for simple framed structures. After an extreme event, it is a valuable resource in determining the safety of a building that may be vulnerable to progressive collapse. In addition, this tool can be used in the design phase of a project, allowing a designer to develop a sense of how a building will respond to an extreme load prior to embarking on a costly finite element analysis.

While the software itself was developed using high-fidelity finite element models, the principles behind the software are gener-



Progressive Collapse Output Summary
Corner analysis
Target column was removed by user.........
Bay support beams / columns.........FAIL
Adjacent Columns .... OK
Progressive Collapse is Limited to First Bay Only.
Remaining Structure Potentially UNSTABLE

Figure 6: Example solution screen showing results of analysis for target column, adjacent structural elements, and overall stability of structure

al, and applicable to all progressive collapse analyses. ProCAT considers the primary target elements, the adjacent bays, and finally the overall stability in determining the progressive collapse potential of the structure.

Analysis, Mitigation and Prevention

There have been many cases in history that have highlighted the dangers associated with the progressive collapse of a building. Recent events have underscored the importance of taking extreme events into consideration in the design of a structure. While it is not practical to retrofit every building in the world to resist every possible threat scenario, it is important to understand how existing structures will respond to these events. The goal is to limit the loss of human life and the extent of localized damage. In addition, it is necessary to ensure the safety of rescue personnel so that they can enter buildings safely and reach the survivors in the event of a disaster.

Design criteria such as those from GSA and UFC provide a means of evaluating and possibly mitigating the damage that would result from a progressive collapse event. These criteria include provisions for designing structures that are better equipped to resist progressive collapse failure. These criteria not only refer to the structure itself but the surrounding area, prescribing standoff distances for typical blast loadings.

It is also the responsibility of the structural engineer to come up with practical design solutions for mitigating progressive collapse damage. Engineers must have an understanding of the fundamental response of the structures that they are designing, so that they can develop solutions that can be implemented without raising the costs of a project to astronomical levels.

Finally, when a disaster does occur, it is necessary to have a rapid means of assessing the safety and stability of the structure. Development of fast-running software tools allows rescue crews to determine whether a building is safe enough to enter, and whether a building is in danger of imminent collapse. These tools can also be used as a rapid assessment tool in the design phase of a project, allowing engineers to get a sense of the structural response to a particular threat scenario.▪

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