Overview

Description

Methodology

CSiProgressiveCollapse considers two possible methods of analyzing a structure:

1. Progressive Collapse Initiation
2. Progressive Collapse Simulation

For each method of analysis, the user can choose one of three methods of design for determining D/C of elements. These methods also affect the brittle versus ductile nature of failure within the structure:

1. Strength-based (using applied building codes)
2. Ductility-based (using hinge rotations)
3. Hinge-based (using user-defined PMM hinges to mimic loss of stiffness and heavy damage before failure)

One or more iterations will be run whereby the loss of the key element is simulated and the specified elements are assessed. For each progressive collapse iteration, the following loads are created:

1. Load pattern & case for applied reactions of removed element
2. Staged construction case where the element is removed, and reactions are applied.
3. Nonlinear direct integration time history analysis where the applied reaction is ramped down over a short time period.

This method allows the member to be removed from the model at the point of failure while maintaining force equilibrium, and then modeling the dynamic shock effects of the member unloading from the structure. This provides a realistic assessment of the structure as the stiffness and deformation of the structure at the time of failure is carried through into the failure analysis, and dynamic impulse effects of the loss of a member are included. **Sources? Any discussion of linear/non-dynamic methods and where this diverges?**

Progressive Collapse Initiation

Progressive collapse initiation is analyzed by removing columns from the key element group, one at a time, and seeing if their removal causes the failure of other critical elements defined in the critical path group.

Decision trees go here

Progressive Collapse Simulation

To better assess if a collapse is truly progressive, or just a general collapse that is unacceptable, it may be useful to track a progressive collapse mechanism beyond the first step of progression. This feature may also be useful for checking 'compartmentalization' strategies.

This analysis method is extremely time intensive and prone to giving erroneous results if the model is not set up carefully, so it should be used sparingly. In order to reduce the scope of analysis, it is recommended to run this feature on one element at a time, and to compile such a list of elements to remove based on results from first running the 'Progressive Collapse Initiation' method first.

Decision trees go here

Strength-Based Design

Strength-based design uses D/C ratios determined from standard building codes to determine member failure. Similar to seismic design, in order to account for the nonlinear and dynamic effects of loading the structure, an overstrength factor should be used in these calculations. There are no specific recommendations for progressive collapse, but if the user selects to use an overstrength factor, they can specify their own. By default if this options is selected, the overstrength factor used in seismic design for the corresponding building code will be used.

This method is the most conservative of the design methods for progressive collapse and considers the structure to essentially remain elastic.

Decision trees go here

Ductility-Based Design

For considering more rare and extreme events that initiate progressive collapse, ductility-based design is often used. This allows for consideration of elements becoming plastic. Depending on how the structure is modeled, this method can also account for softening effects of members as they yield by the inclusion of frame hinges. Such softening effects might change the progressive collapse propagation path.

Decision trees go here

Hinge-Based Design

This method allows the user to attempt to model progressive collapse more realistically by including their own hinge definitions. Such a method can be helpful in simplifying the analysis. It is especially useful for more customized analysis, such as if the user wants to properly include the effects of catenary action in progressive collapse, as this phenomenon drastically changes the moment-curvature relationships of an element.

Decision trees go here

Naming of load cases and models

In order to help the user reference different stages of the progressive collapse results, a naming methodology has been devised. As the user is given the option for the collapse scenarios to be broken up into separate models, models generated from this option will abide by the same naming convention.

The basic naming convention is as follows:

PC_ K001-IT001

- PC - for progressive collapse case
- K001 - first key element in a group checked
- IT001 - first iteration of progressive collapse (for the initiation check, this is always 1).

The zeroes placeholder will be automatically adjusted by the program for convenience in name ordering. The number of digits will depend on the number of elements in the key element and critical path groups. This name will be appended to the existing model name if the analysis is run with the option of saving separate models.

For the load patterns and cases used in the iteration, the convention is as follows:

Name Applies to	**Example Name**
Load Pattern, model (if specified separate models)	PC_ K001-IT001
Staged Construction Case	PC_ K001-IT001_SC
Time History Case	PC_ K001-IT001_NLDITH
Load Combination	PC_ K001-IT001_COMB

CSiProgressiveCollapse auto-generates group names used for the analysis for user convention, although the user can specify their own groups for the same usage. The auto-generated groups are as follows:

Group Type	**Group Name**
Key Element Group	PC_Key
Critical Path Group	PC_Path

Numbering - Greater 0 spaces are verbose. Tailor spaceholders to likely maximum digits needed?

PC Load Iteration Numbering

- **itNum**
- Max num limited by number of elements in PC path group
- Numbering only needs to accrue within a given model if key elements are in separate models.
- However, numbering needs to be unique if separate files are not saved for each key element. Probably best to do it this way

Key Element Numbering

- **keyElemNum**
- Num of 0s depends on number of key elements to be checked, which is known.

Current

PC_**001**-**1**

PC_**001**_SC

PC_**001**_NLDITH

PC_**001**_COMB

Alternative

PC_ **K001**-**IT001**

PC_ **K001**-**IT001**_SC

PC_ **K001**-**IT001**_NLDITH

PC_ **K001**-**IT001**_COMB

Group Labeling

Key Element Group - **PC_Key**

Critical Path - **PC_Path**

Operation

Step-By-Step Procedure

SAP2000 Example

Terminology

Alternate Load Path (AP Method)

If a structural element fails, progressive collapse is averted by loads finding load paths different than those implicitly considered in design. One purpose of considering progressive collapse in analysis is to determine what alternate load paths exist, and whether they can resist the additional loads created by the initial failure. The PC_Path group includes elements that are considered part of the alternate path as a simplifying part of the analysis and design procedures. Members belonging to this group are considered essential to maintaining an alternate load path in addition to normal load paths, and the failure of these elements leads to a progression of a collapse mechanism.

Critical Path

The critical path contains members that are critical to designing for progressive collapse. This consists of 3 member types:

1. Members that are part of the gravity takedown and lateral load systems.
2. Members that are expected to be part of the alternate path that resists progression of collapse.
3. Members that contribute significantly to the floor area collapse, for consideration of compartmentalization allowances in code specifications.

Compartmentalization

Compartmentalization is a method of resisting progressive collapse whereby a limited amount of failure is allowed and possibly explicitly designed for to act as a fuse and energy dissipater. **GSA code limitations on extent.**

For example, in the EuroCode, British, UFC, and GSA standards a building is required to be able to withstand the loss of a single column with collapse limited to a certain square footage or number of stories and bays.

Key Element

Key element is an element that will initiate progressive collapse if it fails. These elements need additional design consideration beyond standard code design to ensure that they do not fail. CSiProgressiveCollapse uses a key element group, composed of one or more members, to identify the key members in a structure. Each member is removed, one at a time, and criteria is checked to determine if the loss of the member results in progressive collapse.

Progressive Collapse

Snippet from thesis. Integrate?

Interactive Measures

Interactive measures fall into indirect design methods such as Alternate Path and Compartmentalization methods. These are considered interactive rather than reactive because they are non-threat specific and are always designed into the structure similarly regardless of the location or severity of the damage, and become engaged only once a key element has failed.

Alternate Path Method (AP)

The alternate path method (AP) is more versatile than SLR as it is not threat specific. Through Alternate Path, a structure can be damaged in any fashion and the remaining structure is expected to redistribute gravity and lateral loads. For example, in the EuroCode, British, UFC, and GSA standards a building is required to be able to withstand the loss of a single column with collapse limited to a certain square footage or number of stories and bays.

Alternate Path methods are often accomplished through additional capacity, continuity, and/or ductility in structural members and the structural system to resist collapse. This can be accomplished through bending (vierendeel action), catenary action, or membrane action. Forces can also be redistributed through outrigger or "hat" trusses at various levels of the building that act to suspend portions of the building above the region of damage. In certain structural systems such as bearing wall construction, the structure can bridge across the damaged area through arching action (Figure 2.18). Critical beam-column connections and panel zones may also be protected from stress overload to aid in Alternate Path by construction details.

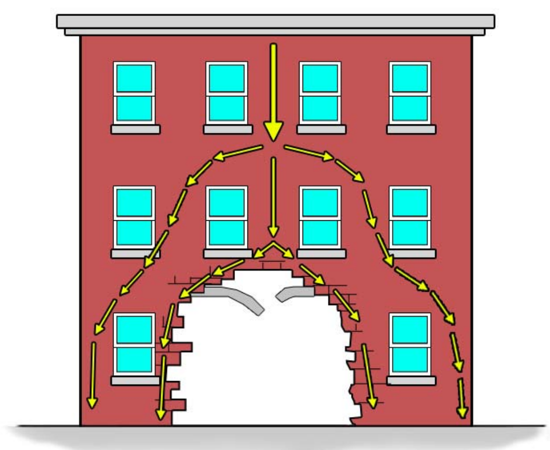

Figure 2.18: An arching action form of Alternate Path progressive collapse resistance

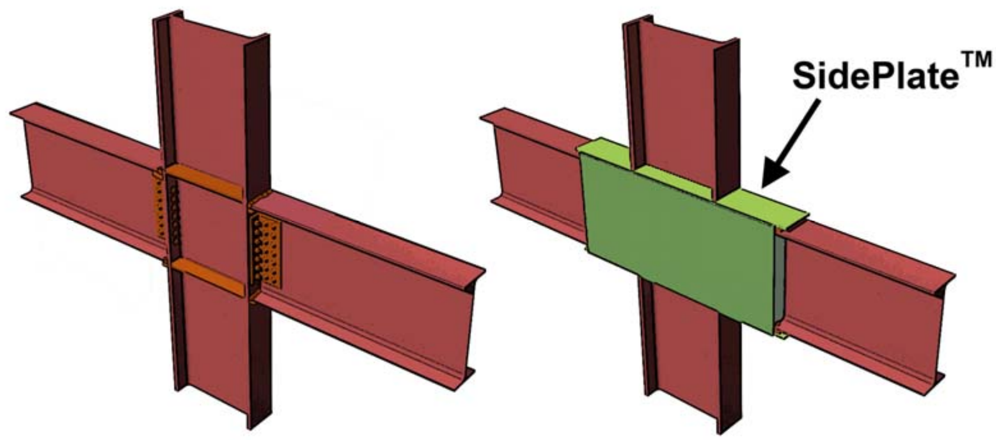

Figure 2.19: AP techniques for ensuring load transfer through connections

The Alternate Path method does have downsides. It is difficult to confirm through analysis as nonlinear geometry, nonlinear material response, and dynamic response must all be considered to different degrees. The method may still require substantially greater material or expensive detailing. Additionally, there are many locations or combinations of locations in a building that can initiate progressive collapse through their failure. This exponentially increases the amount of computation needed to determine the resistance of a building to progressive collapse. This problem can be reduced by only considering columns that have the greatest effect on the building (e.g. checking a corner column, a column in the center of the building, and a column in the center of the face of a building), or those most likely to be damaged (e.g. limiting considerations for damage occurring at the lowest 2 floors) (Figure 2.20).

A more serious problem is that the continuity required to achieve Alternate Path may actually *encourage* progressive collapse! This occurs through overloading neighboring elements, thereby "unzipping" the structure. It can also topple neighboring elements as their stability is reduced by the propagating damage. These dangers must always be considered when designing a building using the Alternate Path method.

Compartmentalization

A less common consideration for mitigating progressive collapse is to compartmentalize a structure. Collapse from an extreme load is allowed in a limited area, but the propagation is halted by fuses in the structure, which are created either through weakness in the structure (e.g. expansion joints) or through stiffened areas of the structure that act to concentrate stresses, forcing fracture at the stiffness discontinuities (e.g. shear walls, spandrels).

Such a measure would be easier to analyze as the failure is more brittle, and the progression of forces doesn't need to be tracked as far as it does in the Alternate Path method. It is also likely to be the cheapest method as it can be implemented

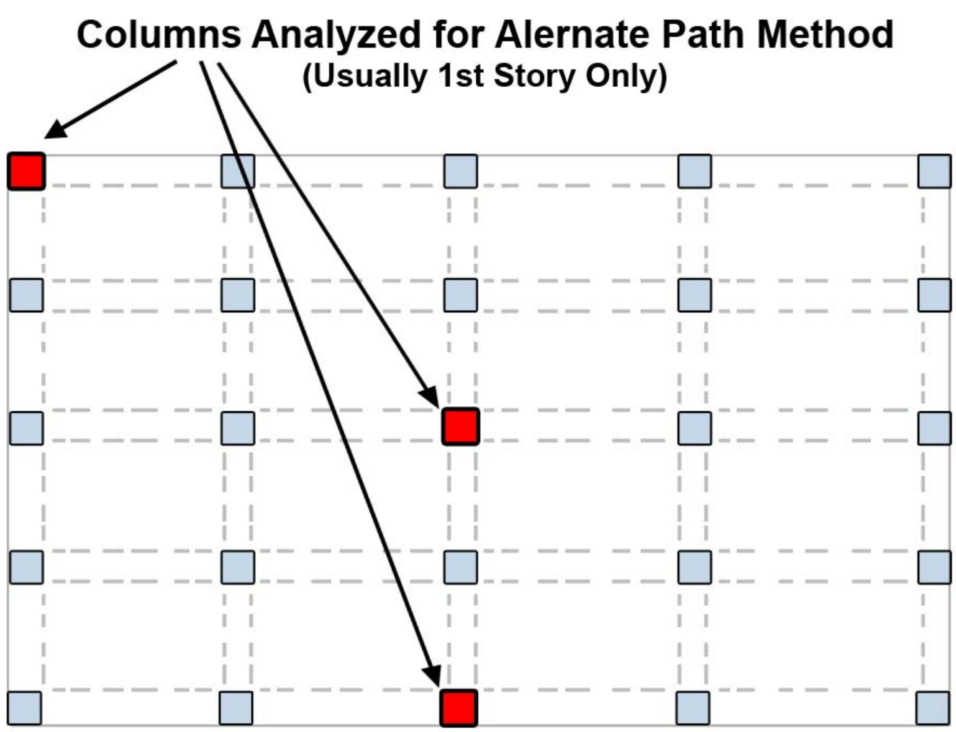

Figure 2.20: Progressive collapse initiation areas usually considered for Alternate Path method

through less structure, or through strategic variations in the existing structure, as opposed to additional material or detailing.

Compartmentalization is more limited, though, as in buildings such a measure could be difficult to control without a collapse resulting in a pancake progressive collapse mode. It is more feasible in bridges or in low-rise structures