Evaluation of Design Approaches for Progressive Collapse

David STEVENS
Senior Principal
Protection Engineering Consultants
Spring Branch, TX, USA
dstevens@protection-consultants.com

Kirk MARCHAND
Managing Principal
Protection Engineering Consultants
Spring Branch, TX, USA
kmarchand@protection-consultants.com

Brian CROWDER
Structural Engineer
NAVFAC Atlantic.
Norfolk, VA, USA
brian.crowder@navy.mil

Ed CONRATH
Structural Engineer
US Army Corps of Engineers
Omaha, NE, USA
ed.j.conrath@usace.army.mil

Tim CAMPBELL
Structural Engineer
US Army Corps of Engineers
Omaha, NE, USA
timothy.c.campbell@usace.army.mil

Summary

Progressive collapse design approaches typically incorporate direct and indirect methods. Direct design techniques include the Alternate Path and Specific Local Resistance methods, in which collapse is explicitly considered during the design process. In indirect design, resistance to progressive collapse is incorporated implicitly through prescriptive requirements for strength and continuity, typically in the form of Tie Forces. These methods were recently re-evaluated and revised, in support of revisions to the Department of Defense Unified Facilities Criteria (UFC) 4-023-03 *Design of Buildings to Resist Progressive Collapse*. The research and analyses for revisions to the indirect and direct methods are reported in this paper.

Keywords: Progressive collapse, direct design, indirect design, tie forces, alternate path, specific local resistance.

1. Introduction

Progressive collapse is a relatively rare event as it requires both an abnormal loading to initiate the local damage and a structure that lacks adequate continuity, ductility, and redundancy to resist the spread of damage. However, significant casualties can result when collapse does occur.

For the direct design approaches, progressive collapse is explicitly considered during the design process. These approaches include the Alternate Path method, in which the building bridges over a missing structural element, and, the Specific Local Resistance method, in which the building is designed for a specific load or threat. In indirect design, resistance to progressive collapse is implemented through prescriptive requirements, typically in the form of Tie Forces, which insure a minimum tensile strength in horizontal and vertical structural members and connections.

During the revision of UFC 4-023-03, the effectiveness of the indirect and direct design methods was evaluated and research and analysis was performed to revise these approaches. The research, analyses, and improvements for the indirect and direct methods are summarized in this paper.

2. Tie Forces

In the Tie Force approach, tensile force capacities must be provided by the structural members and their connections. The Tie Force requirements in the current UFC 4-023-03 are based on those developed by the British after the Ronan Point collapse and these requirements continue to be used in the current Eurocode. The physical motivation for the tie force magnitudes and locations was originally based on an assumed catenary response of reinforced concrete structural members and slabs above a removed column. The sag at the point of column removal was assumed to be 10% of the double span length (20% of the single span). Tests were performed to verify that reinforced concrete elements could provide the required tie forces while undergoing this level of deformation.

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However, the general approach was extended to other materials, such as steel and masonry, and questions on the applicability have since been raised. In particular, typical steel connections are not capable of providing the rotations that are required to develop catenary forces. Therefore, we now propose that the floor system, instead of the beams, girders, and spandrels, be used to provide and carry the internal and peripheral tie forces. Properly detailed, floor systems are strong and ductile structural elements that can absorb significant energy while undergoing large rotations. In this approach, the floor system in the damaged portion of the structure will transfer the vertical loads via catenary or membrane action back to the undamaged horizontal members, which, in turn, will transfer the load into the vertical elements. The floor system, often considered as a secondary member, will support the primary damaged structural elements.

3. Alternate Path

For the Alternate Path approach, the designer must demonstrate that the structure can bridge over a removed vertical load-bearing member. Four main requirements must be specified in this approach: 1) the size and location of the removed element, 2) the loading, 3) the acceptance criteria for the members and connections, and 4) the acceptance criteria for the overall structural performance.

Some issues and opportunities for improvement in the analytical methods and the acceptance criteria in the original UFC 4-023-03 were identified by the users. A careful review of these issues and an assessment of available design methodologies for severely loaded structures resulted in the adoption and adaptation of the approaches and criteria employed in ASCE 41-06 Seismic Rehabilitation of Existing Buildings. ASCE 41-06 provides a very comprehensive, detailed and vetted approach to the design of structures that undergo severe deformations due to dynamic loadings. While ASCE 41-06 addresses seismic loads, which are horizontal and transient, much of it can be incorporated into progressive collapse design, where the loads are vertical and permanent.

The applied loads were also carefully considered in the revision of UFC 4-023-03, in particular, the load increase factor to account for both nonlinear and dynamic effects. Previously, a factor of 2 was applied to the static load, for both Nonlinear Static (NS) and Linear Static (LS) analysis. Since a NS model includes nonlinearity by definition, it is inconsistent to use the same factor for both LS and NS models. Thus, a significant effort was undertaken to develop appropriate Load Increase Factors (LIFs) for LS models, such that the dynamic and nonlinear effects are approximated, and, Dynamic Increase Factors (DIFs) for NS models, such that the dynamic effects are included. To determine the LIFs and DIFs, a series of reinforced concrete and steel building models were developed and analyzed with SAP2000. The results were used to define the LIFs and DIFs as functions of the allowable plastic rotation angle, which is based on the structural performance level specified in UFC 4-023-03. The DIFs are 2.0 or less and typically below 1.5; the values of the LIFs are much higher than 2, but are also counterbalanced by the increase in the design strength using the "m-factor" approach similar to that employed in ASCE 41.

4. Specific Local Resistance

While the requirements in UFC 4-023-03 were developed independent of a specific action or threat, the initial motivation of DoD in developing the UFC was to protect against an explosive attack. Although design methods for hardening structural components exist, the main difficulty lies in determining the level of threat (explosive weight and standoff). Government agencies are hesitant to prescribe values since each situation is different; in addition, if specific threats were defined, the information would be classified, hindering its dissemination to the design community. Therefore an approach independent of a specific explosive threat was developed to enhance the performance of perimeter columns and walls for the first and second story, such that perimeter column and wall flexural performance is increased above that "expected" for the gravity/lateral based structural system, thus increasing the implicit level of blast protection.

5. Conclusions

In the proposed revisions to UFC 4-023-03, the effectiveness of the indirect and direct design methods was re-evaluated and research was performed to improve these approaches. The resulting revisions to UFC 4-023-03 represent a significant improvement over the first version.