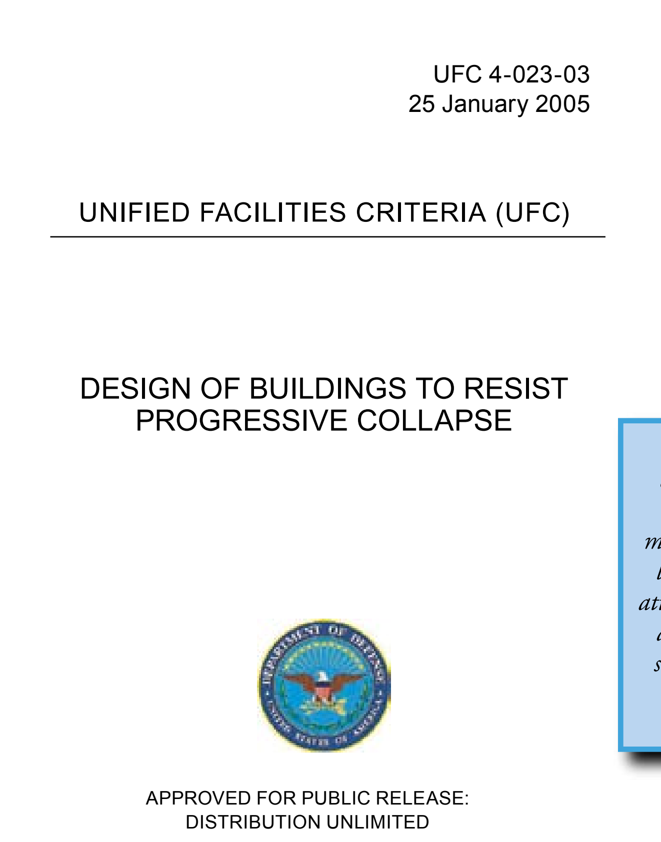
UFC 4-023-03
25 January 2005

UNIFIED FACILITIES CRITERIA (UFC)

DESIGN OF BUILDINGS TO RESIST PROGRESSIVE COLLAPSE

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Figure 1: UFC 4-023-03

UFC 4-023-03: Design of Buildings to Resist Progressive Collapse

A Review and Update on Department of Defense Progressive Collapse Guidance

By Kirk A. Marchand, P.E., David J. Stevens, PhD, Brian Crowder, P.E., and Tim Campbell, P.E.

The United States government is perhaps the largest building owner in the world. The design of government buildings typically follows consensus building codes and standards of practice. However, the performance expectations for these facilities and the risks they may be exposed to may differ significantly from a private facility. Terrorist attacks over the last 20 years have focused the government's attention on the potential for a higher risk of attack on government buildings. The variability of the terrorist threat also pointed out that a structure thought to have no significant risk of attack at the time of construction could suddenly become a target, or be located near a target, as the threat environment changes. Additionally, there are concerns that characteristics of modern structures could lead to damage and injury disproportionate to the initiating attack.

As part of a program to reduce the likelihood of mass casualties following an attack, the Department of Defense (DOD) developed interim guidelines in 1999 and 2001 to reduce the risk of progressive collapse. These threat independent guidelines were developed to provide resistance to collapse propagating outside of a local collapse region. DOD has separate design guidelines for protecting a facility against a specific threat.

In 2004, DOD began an effort to develop a Unified Facilities Criteria (UFC) on the *Design of Buildings to Resist Progressive Collapse* (UFC 4-023-03, *Figure 1*) to provide designers of its facilities with specific, enforceable design criteria for mitigation of progressive collapse due to blast, severe impact or other natural or man made events. In an effort to update and expand the DOD Interim guidelines, the DOD researched and then adapted the best available approaches from different organizations and countries. The content was expanded to provide criteria for typical DOD construction including concrete, structural steel, masonry, cold formed steel, and wood.

The existing guidelines and standards researched included ASCE7-05, *Minimum Design Loads for Buildings and Other Structures*. ASCE7-05 contains general performance requirements for structural integrity (ASCE 7-05 Para. 1.4), but like other building codes and material specific design codes, does not contain specific design criteria to meet these requirements or resist progressive collapse. Aside from DOD interim guidance published in 2000, the only existing guidance available in the US was the recently developed GSA progressive collapse design requirements, *Progressive Collapse Analysis and Design Guidelines for New Federal Office Buildings and Major Modernization Projects*, published in June 2003. British regulations based on both indirect and direct design approaches were also researched. The indirect design approach requires the development of minimum ties, or continuity, in the structure in specific locations. The tie requirements are material specific and contained within the material codes. The two direct design approaches include the Alternate Path Method (APM), in which the building must be designed to span over a missing element, and Specific Local Resistance (SLR) in which key members must be designed to withstand a significant static pressure loading. Other European countries have utilized similar procedures. The development of the PC UFC drew heavily on the British approach with some influence from the GSA guidelines.

Risk Based Design

The UFC employs a "combined approach", first suggested by Ellingwood and Leyendecker in 1977. In this approach, indirect design is used for "normal" buildings by specifying minimum levels of strength, ductility, redundancy, and continuity. If the building is "unusual" or the consequences of a progressive collapse event are severe, then explicit consideration of the resistance to progressive collapse must be considered through a direct design approach. This combined approach is thought to add minimal expense while significantly improving the ability of structures to resist progressive collapse. It was determined that the British approach of indirect design utilizing tie forces would be appropriate for "normal" DOD buildings. The Alternate Path Method (APM) applied concurrently with indirect design was deemed appropriate for "unusual" DOD buildings.

The definition of a "normal" or "unusual" building corresponds to the definition of a level of protection (LOP) required for the building. Using UFC 4-020-01 *Security Engineering Facility Planning Manual*, a DoD project planning team determines the LOP. The LOP considers the value of assets, the occupancy, mission criticality, and other factors. The specific design requirements depend upon the required LOP. For Very Low LOP (VLLOP) and Low LOP (LLOP), only ties are required. For Medium LOP (MLOP) and High LOP (HLOP), both ties and APM are required. Most DOD structures will require Very Low or Low LOP. UFC 4-023-03 design requirements are set in an LRFD format, which is appropriate for a risk-based approach.

Tie Force Provisions

In the indirect design tie force approach, the building is mechanically tied together, enhancing continuity, ductility, and residual strength through the activation of catenary resistance in the structure. Tie forces are typically provided by the existing structural elements and connections that are designed using conventional design procedures to carry the standard loads. *Figure 2* shows tie locations and function.

Ties consist of internal, peripheral, external

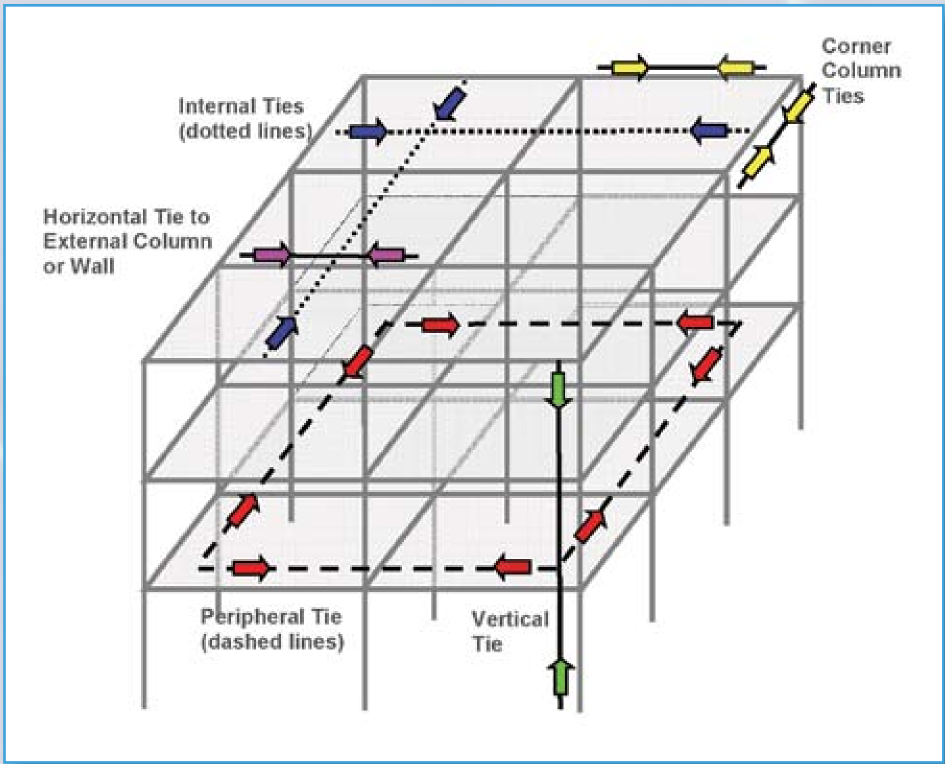

Figure 2: Tie location and function

and corner wall/column, and vertical tension elements. Ties are intended to provide a residual tensile capacity available in members and connections after flexural response (bending and load redistribution) has occurred in a structural system.

The load path for peripheral ties must be continuous around the plan geometry. For internal ties, the path must be continuous from one edge to the other. Likewise, vertical ties must be continuous from the lowest level to the highest level of the building. Along a particular load path, different structural elements can provide the required tie strength, providing that they are adequately connected. For example, internal tie strength may be provided by a series of beams on a beam line, provided that the connections to the intermediate elements (girders, beams or columns) can provide the required tie strength. Tie force calculations are simple, requiring combination of easily identified structure characteristics (tie span, bay width of the structure and number of stories in the structure) with a basic required tie force.

Alternate Path Method

In the alternate path method (APM), the structure must be capable of bridging over a missing column or bearing wall by transferring the loads along alternative load paths. In UFC 4-023-03, structural analyses must consider the "removal" of external columns near the middle of the each side and at the corner of the building. Columns must also be removed at locations where the plan geometry of the structure changes significantly or at locations where there is an abrupt change in loads, member geometry, or bay sizes. *Figure 3a* illustrates column removal strategies for buildings without public interior spaces. *Figure 3b* illustrates column removal approaches where interior spaces are uncontrolled (public).

The column or wall is removed from the structural model without degrading the capabilities of the joint at the upper end of the member. Physically, this may be unlikely depending on the type of event causing the damage. Critics of this approach usually refer to this form of column removal as the immaculate removal. However, APM is not intended to replicate an actual event; the goal is to verify that the structure has satisfactory flexural resistance to allow bridging across an area with localized damage.

The GSA guidelines require only removal of ground floor elements while UFC 4-023-03 requires that analyses be performed for each floor, one at a time. The motivation for the DOD requirement is that facilities could be attacked with direct or indirect fire weapons, which could damage a structure at upper floors. Since some buildings may be more susceptible to progressive collapse from damage at higher elevations (due to the reduced reserve capacity from the fewer number of floors above), this requirement will motivate the designer to distribute additional strength and ductility to upper levels.

The load case for nonlinear dynamic APM analysis is taken from ASCE 7-02, Section C2.5, *Load Combinations for Extraordinary Events*. For linear and nonlinear static analyses, a dynamic load factor is mandated that doubles the gravity loads for the bays adjacent to and above the removed element. This factor approximates the potential inertial effects in the area of local collapse and comparison to advanced analysis techniques has shown it is generally conservative.

Allowable limits of the extent of damage for the removal of a wall or column are set in the PC UFC. If damage exceeds that specified in the UFC, or any structural element or connection violates acceptability criteria, modifications must be made to the model before the analysis continues. Acceptability criteria for strength and deformation are included for each material. A structural design is deemed to provide satisfactory resistance to progressive collapse if, at the final analysis time step, the damage is within the allowable damage limits and the individual structural elements meet the acceptability criteria.

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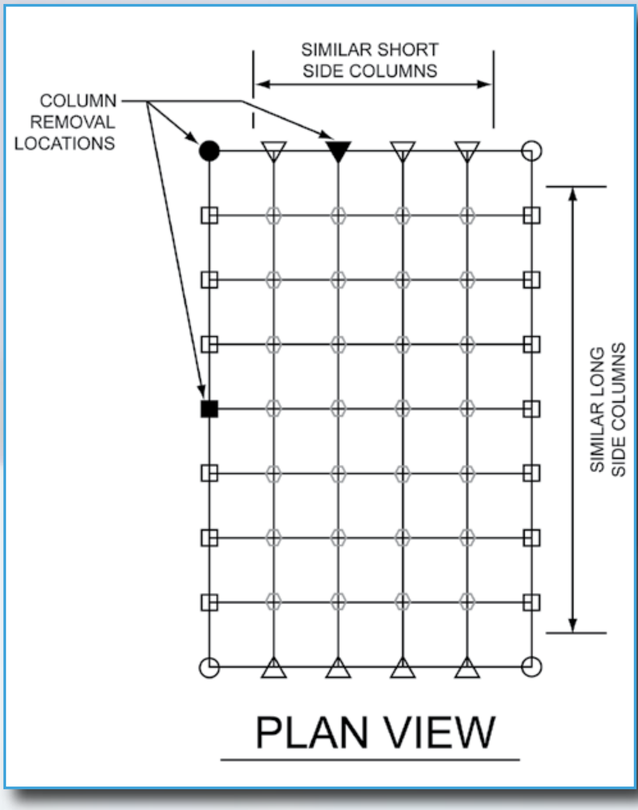

Figure 3a: Column removal approaches for buildings with non-public interiors

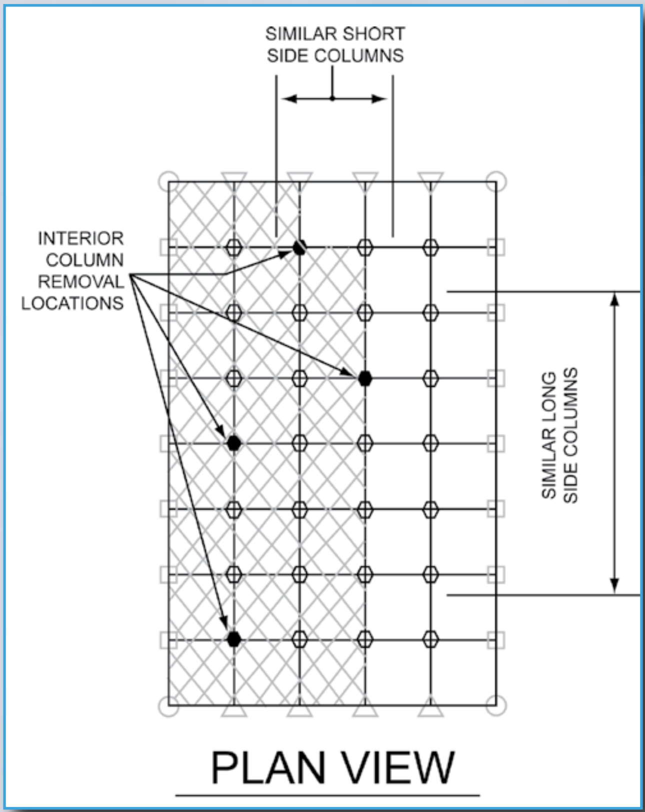

Figure 3b: column removal requirements for buildings with public interiors

Additional Requirements

DOD has additional prescriptive requirements that increase resistance to progressive collapse. For all Levels of Protection:

- All multistory vertical load carrying elements must be capable of supporting the vertical load after the loss of lateral support at any floor level (i.e., a laterally unsupported length equal to two stories must be used in the design or analysis). The loads from the "removed" story need not be applied to the wall or column.
- All floors and roofs must be able to withstand a prescribed net upward load applied to each bay. The uplift loads are not applied concurrently to all bays.

For Medium and High Levels of Protection:

- All perimeter columns must have sufficient shear capacity to develop the full plastic flexural moment.

Impact of the Criteria on Design Complexity and Cost

Analysis and design for tie forces can be completed using simple hand calculations or automated tools. Using standard analysis software for linear static APM is relatively straightforward and can be automated (*Figure 4*). The dynamic analysis procedure is more complex, and the design tends to be iterative. Detailing is critical, particularly for concrete, since reinforcement must be provided for bridging conditions at beam-column intersections.

Preliminary results from cost analyses performed on load bearing and framed structures suggest that costs to incorporate a Low Level of Protection (indirect design approach) are a very modest 0.2% of total construction costs for RC and steel framed buildings and 2-5% of total costs for wood, masonry and cold-formed steel buildings. Costs for Medium Level of Protection involving APM are 2-5% of total cost for RC and steel framed buildings and 5-10% of total cost for wood, masonry and cold-formed steel load bearing structures.

Some Limitations, Questions and Current Development

While tie forces will be the most common measure employed in most DoD structures, the actual mechanisms by which they will limit collapse are the least understood. Some recent high fidelity numerical analysis may suggest that ties, as prescribed in the current UFC, do provide mitigation of progressive collapse through catenary action, but do not protect all areas of the building equally. This, however, may be acceptable at a low level of protection.

The same high fidelity analysis also showed that the procedures specified for medium level of protection (ties and alternate path analysis) provided significant protection in actual blast load event scenarios. In this "dirty" environment, where floor damage occurs simultaneously with column loss, the medium level design approach was shown to be effective (*Figure 5*).

Research, including additional numerical analysis and full-scale testing is planned to continue to address improvements in the criteria approach.

The Future of UFC 0-023-03 and Progressive Collapse Criteria and Design Standards

The DOD UFC document and the GSA Progressive Collapse Guidelines have developed separately, but are similar in many ways. Future efforts may attempt to merge these documents into a single federal standard for progressive collapse mitigation. Other national organizations such as the National Institute of Science and Technology (NIST) are working to develop guidance that may one day be adopted into national building codes.

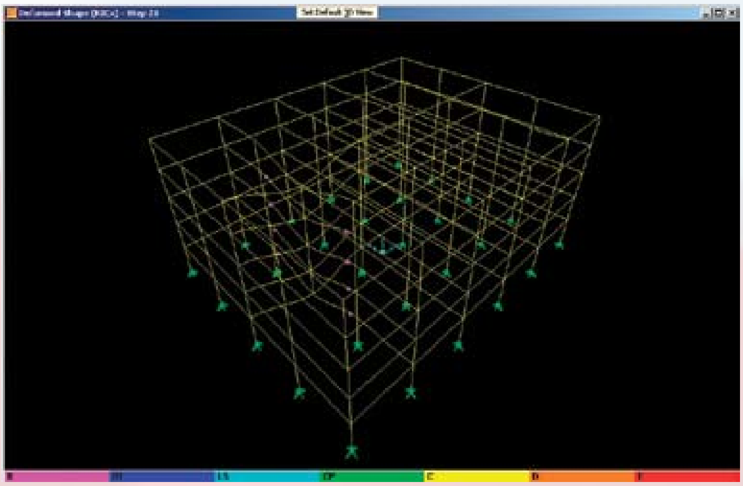

Figure 4: 4x5 bay, example 5 story structure nonlinear hinge rotations in initial alternate path analysis

The U.S. Government has become a building owner that requires specific attention to structural integrity and resistance to progressive collapse. The structural engineering community should consider the need for similar risk based criteria within future consensus standards. These provisions should be evaluated not only as a measure to mitigate a terrorist threat but as a way to improve the safety and performance of our structures for all extreme events. Since the 1970s, engineers have expressed concern about continued optimization in structural design and the trend to speed erection during construction. These trends can lead to reduced robustness and continuity in the structural system. In 1975, Professor John Breen of the University of Texas, when commenting on current approaches to structural design, said that "…it was certainly possible to design statically determinate structures in conformance with existing codes." In general, the degree of indeterminacy incorporated in modern structures is being minimized for ease of construction and economy. This exposes structures to a greater risk of progressive collapse when the unexpected occurs. It is now appropriate to provide designers specific guidelines to ensure the level of structural integrity mandated in ASCE7.

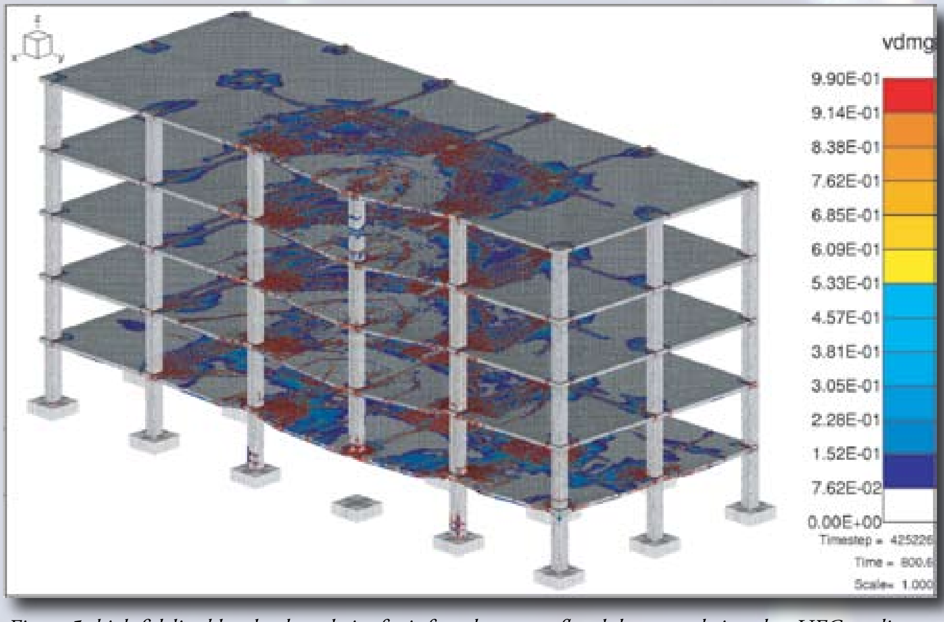

Figure 5: high fidelity blast load analysis of reinforced concrete flat slab system designed to UFC medium level of protection (courtesy of Weidlinger Associates, New York and the Defense Threat Reduction Agency)

UFC 4-023-03, which includes a commentary with additional background and guidance, can be obtained at **www.wbdg.org/references/pa_dod.php**. This webpage also provides the opportunity to submit "Criteria Change Requests" if you have comments or suggested modifications.▪

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