RECENT DEVELOPMENTS IN PROGRESSIVE COLLAPSE DESIGN

David Stevens[1*], **Eric Martin**[2], **Eric Williamson**[3], **Aldo McKay**[1] **and Kirk Marchand**[1]

[1]*Protection Engineering Consultants, San Antonio, Texas*
[2]*US Army Corps of Engineers, Protective Design Center, Omaha, Nebraska*
[3]*University of Texas at Austin, Austin, Texas*
* *Corresponding Author (dstevens@protection-consultants.com)*

Abstract

The state-of-the-art in the design of buildings to resist Progressive Collapse (PC) has continued to advance, in North America and throughout the world. Recent developments include improved design guidance, cost assessments for implementing PC design requirements, research efforts to understand key structural mechanisms for collapse resistance, and growing experience in using commercially-available design tools to better design and analyze progressive collapse events. The goal of this paper is to report upon these recent developments.

Keywords: Progressive Collapse Design, Extreme Events, Structural Testing.

1. INTRODUCTION

Progressive collapse design of buildings continues to be an active area of research and development. Not only is the topic important in terms of protecting building occupants but it is also an intellectually-engaging issue, with a wide spectrum of views, ranging from those who feel progressive collapse design is not needed to those who have an obligation to protect the public. The range of technical issues is quite broad also, as there are many types of structural systems and materials, the structural response is typically complex and nonlinear, and there are a number of analysis and design approaches that can be taken. Finally, there is also passionate discussion generated by those who mistake progressive collapse design for hardened structure design, those who propose risk-based approaches when it is known that there is insufficient data to assess risk and those who feel progressive collapse design should not be employed until more research is done and all answers are known.

Research into progressive collapse (PC) is ongoing in the United States (US) and Canada. As part of ongoing efforts by the US Department of Defense (DoD) to better protect its personnel, Unified Facilities Criteria (UFC) 4-023-03 *Design of Buildings to Resist Progressive Collapse* has recently been improved. Test programs are ongoing in North America, including tests of full-scale reinforced concrete and steel structures as well as additional test and analysis efforts at universities and government agencies. Finally, commercially-available structural design software, such as SAP2000 and ETABS, are often used to design for progressive collapse, following the applicable design requirements such as UFC 4-023-03. SAP2000 can also be used as an analysis tool and can provide similar or better results than those determined with high-fidelity physics based (HFPB) tools. A brief summary of these efforts are provided in this paper.

2. DEVELOPMENTS IN UFC 4-023-03 DESIGN OF BUILDINGS TO RESIST PROGRESSIVE COLLAPSE

2.1 Overview of UFC 4-023-03

The development of UFC 4-023-03 *Design of Buildings to Resist Progressive Collapse* was initiated by the US DoD in 2003. The DoD had developed earlier PC design guidance in response to the Oklahoma City bombing [1] but desired a more comprehensive approach after the World Trade Center attacks. There have been two major versions of UFC 4-023-03, with the first release in 2005 [2] and the second in 2009 [3]. The 2009 version of UFC 4-023-03 has recently been modified as discussed later in this paper.

The motivation for the development of UFC 4-023-03 was the lack of progressive collapse design guidance within the US civilian design community. The design of US government facilities typically follows consensus civilian building codes and standards of practice, which were not available for progressive collapse design. As a result, the DoD, was forced to develop criteria to reduce the vulnerability of structures to progressive collapse.

It is important to understand that the US DoD progressive collapse design requirements are threat independent and not intended to explicitly address a terrorist explosive attack; recognition of this fact has eluded a number of engineers and academics who mistakenly think otherwise. UFC 4-023-03 is used to design buildings to resist progressive collapse when the action or threat is unknown/un-foreseen, such as truck impact, internal gas explosions, etc. Since these actions are unknown, a minimal initiating action is required for the design, such as removal of a column or section of wall. If an actual design threat is known (perhaps developed as part of a risk/vulnerability study), the designer can use other US DoD UFCs or similar guidance, to design buildings to resist this threat.

Another key aspect of the US DoD progressive collapse design philosophy is that *the required level of progressive collapse design is based on the consequences of an event*. Progressive collapse, for both foreseen and unforeseen actions, has historically been an extremely low probability event, as it requires an abnormal initiating event and a building that lacks robustness and ductility. The database of progressive collapse events is sparse and is not suitable for defining risk or, consequently, for performing cost/benefit studies, since risk reduction is the only benefit and it cannot be calculated. Again, this fact eludes those who have not studied and understood the issues.

Both versions of UFC 4-023-03 draw heavily upon the overall approach developed by the United Kingdom (UK), after the Ronan Point apartment collapse in 1968 [4]. The effectiveness of the UK approach was validated by the satisfactory performance and reduced casualties for buildings that were designed with the UK approach and subsequently attacked by the Irish Republican Army. The UK approach has been implemented in building codes throughout the world, including Europe, the United States, Singapore, Australia, Canada, etc.

UFC 4-023-03 incorporates two general approaches to progressive collapse design: 1) indirect design, in which the resistance to progressive collapse is increased through the specification of minimum levels of strength, continuity, and ductility and 2) direct design, in which the structure is designed to resist progressive collapse, given a prescribed initial state of damage. The intent of each approach is to increase the ability of a structure to redistribute load or develop additional mechanisms of response following damage. Again, the goal is to provide improved resistance to progressive collapse when the initiating event is unknown and, therefore, an initial level of damage must be prescribed, such as column or wall section removal. This level of initial damage has been misinterpreted by some who continue to mistakenly view progressive collapse design as an exercise in structural hardening.

Indirect design is typically accomplished through the specification of Tie Forces (TFs), which transfer the loads from the damaged portion of a structure to the undamaged portion. TFs are used to mechanically tie a building together, enhancing continuity, ductility, and development of alternate load paths; see Figure 1. In the 2005 version of UFC 4-023-03, the tie forces were taken directly from the British building codes, as developed after the Ronan Point failure [4] and which have been used as the basis of the TFs in the current Eurocode [5]. In the development of the 2009 UFC 4-023-03, the TF approach was re-examined, due to the recognition that steel connections and some reinforced concrete (RC) connections and members are not able to carry the tie force magnitude after being subjected to significant rotations. In the 2009 UFC 4-023-03, the TFs are carried in the floor or roof system and are no longer permitted to be concentrated in the beams, girders and spandrels. Thus, the floor system will transfer the vertical loads via catenary or membrane action to the undamaged horizontal members (beams, girders, and spandrels), which, in turn, will transfer the load into the vertical elements (walls and columns). The floor system, often considered as a secondary element, is now used to support the damaged primary structural elements. To develop the tie forces requirements, as series of finite element simulations were performed on moment resisting frames, using the column removals shown in the right of Figure 1 [6].

It is noted that the TF approach in the 2009 UFC 4-023-03 is actually based on the direct design method (discussed next), as the TF magnitudes were derived from Alternate Path type analyses of a structure with initial damage (column or wall section removal). Thus, it is perhaps more correct to refer to TFs as a subset of the direct design method.

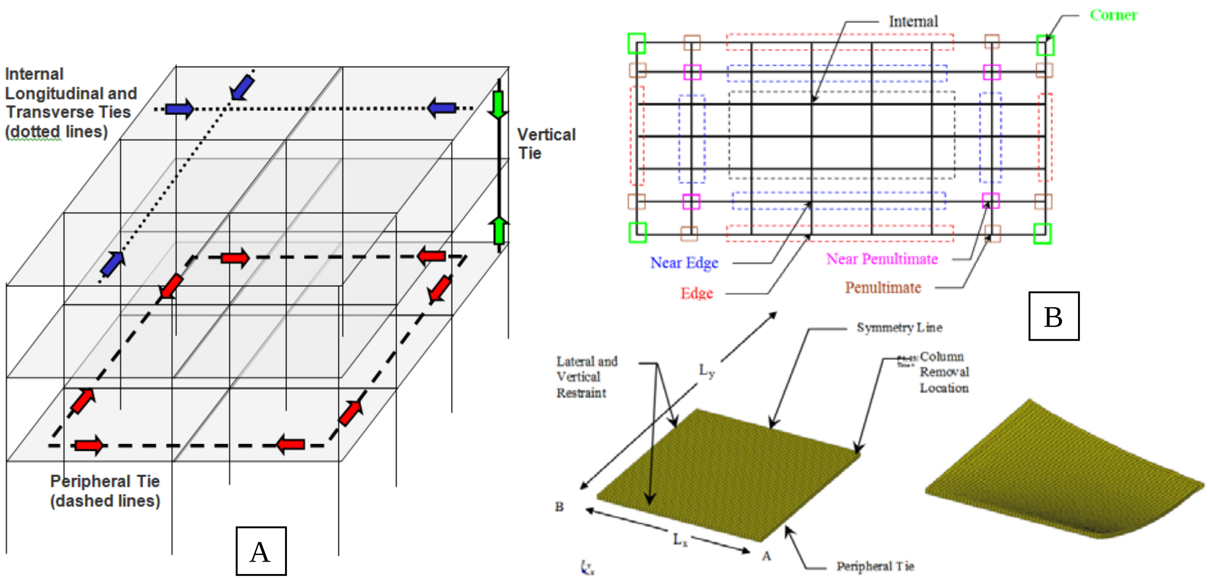

Fig. 1: Tie Forces: A) Required by UFC 4-023-03, B) Column Removal Locations and LS-DYNA Model Used to Determine Tie Forces

Direct Design approaches include explicit consideration of resistance to progressive collapse during the design process and two methods are typically employed: 1) the Alternate Path (AP) method, which requires that the structure be capable of bridging over a missing structural element, with the resulting extent of damage being localized, and 2) the Specific Local Resistance (SLR) method, which requires that the building, or parts of the building, provide sufficient strength to resist a specific load or threat. SLR is used within the UK buildings codes and was modified for the 2009 UFC 4-023-03 where it is referred to as Enhanced Local Resistance (ELR); the advantage of the ELR approach is that a specific threat is not defined as this information can be used by an aggressor to determine the size and type of an effective threat.

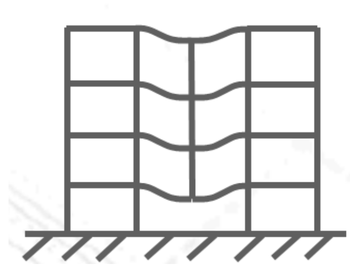

Figure 2. Flexural Bridging for Alternate Path

In the AP method, the designer must show that the structure is capable of bridging over a removed structural element and that the resulting extent of damage does not exceed the damage limits; bridging can be accomplished by flexural resistance as shown in Figure 2, by catenary forces as used in Tie Forces, by Vierendeel truss action, etc. In the 2005 UFC 4-023-03, three analysis procedures were permitted: Linear Static, Nonlinear Static, and Nonlinear Dynamic.

These three AP analysis procedures and the associated acceptance criteria were re-evaluated and significantly modified from the 200f to the 2009 UFC 4-023-03. An assessment of techniques in the related field of seismic design revealed that the procedures and acceptance criteria specified in ASCE 41-06 *Seismic Rehabilitation of Existing Buildings* [7] could be adopted and modified for application in the 2009 UFC 4-023-03. ASCE 41-06 provides a comprehensive 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 ASCE 41-06 could be incorporated into progressive collapse design, where the loads are vertical and permanent. One particular advantage to the use of ASCE 41-06 is that explicit requirements and guidance for multiple building types for each material are provided. Another advantage is that the acceptance criteria and modeling parameters can be scaled for different structural performance levels. Guidance on force-controlled (brittle) and deformation-controlled actions (ductile), primary and secondary components and elements, expected and lower bound strengths, material properties, and component capacities is provided. With a few notable exceptions, the acceptance criteria for linear and nonlinear approaches and the modeling criteria for nonlinear approaches from ASCE 41-06 are used in the 2009 UFC 4-023-03. The ASCE 41-06 criteria are considered to be conservative when applied to progressive collapse design as they have been developed for repeated load cycles (i.e., backbone curves) whereas only one half-load-cycle is applied in progressive collapse. The notable exceptions/modifications to the acceptance and modeling criteria include RC beams and slabs and a number of steel connections. These changes were motivated and justified by experimental data and numerical analysis results. The details are provided in the 2009 UFC 4-023-03.

As described in the next two sections, the US DoD recently improved UFC 4-023-03 with a number of modifications and also performed a cost study to estimate the increase in building cost when progressive collapse design per the 2009 UFC 4-023-03 is implemented.

2.2 Improvements to UFC 4-023-03

After two years of application of the 2009 UFC 4-023-03, the US DoD implemented a number of significant modifications and improvements. These include:

- **Revised peripheral tie force equations**. In the 2009 UFC 4-023-03, façade loads were indirectly applied to the calculation of the peripheral tie forces for framed and two-way load-bearing wall buildings, by spreading them out into a 3-ft width and adding to the areal loading; in some cases, this resulted in a very large peripheral tie force. As part of the recent modification of UFC 4-023-03, the effect of the façade load was numerically investigated with finite element models similar to that shown in Figure 1 [6]. An examination of the numerical modeling results showed that the peripheral tie force should directly include façade loading; the resulting peripheral tie force equation resulted in smaller forces. In addition, the internal and peripheral tie force requirements for one-way load-bearing walls were also re-examined using finite element models and the results showed that both the wall loading and any façade loading must be included in the peripheral tie force requirements.
- **Revised applied loads**. Two aspects of the LRFD-type extreme load combination rarely affected the design of the building but created some confusion and, in some cases, significant extra computational effort. The first change was to remove the 0.9 factor from the gravity loads, so that G = (~~0.9 or~~ 1.2) D + (0.5 L or 0.2 S). In the second change, the lateral load requirement (for all 4 sides of a building) was removed; thus, $\boldsymbol{L_{LAT} = 0.002\Sigma P}$ is no longer applied to the building, reducing the amount of required analyses by 75%.
- **Clarified definition of controlled public access.** Per UFC 4-010-01 *DoD Minimum Antiterrorism Standards for Buildings* [8], controlled public access is now defined as electronic access control devices or mechanical locks on all exterior doors. Where visitor processing makes locking entrances impractical, guards who control visitor access can be considered positive control at those entrances.
- **Added cold-formed steel example**. A cold formed steel example was added as Appendix G; the plan and elevation layout are similar to the wood example in Appendix F. The alternate path method with hand calculations is employed for a number of wall removal locations.
- **Revised example problems for secondary component checks for the linear static method**. In the linear static method for alternate path design, secondary members must be checked against the appropriate acceptance criteria, just as for primary members. This check can be performed in a number of ways and the example problems in the appendices were modified to clearly demonstrate the process.
- **Clarified live load reduction requirements**. Live load reduction (LLR) is still allowed in the revised UFC 4-023-03, but the requirements have been made more explicit. For framed structures, the analyst may use the LLR for each beam individually or may use the same LLR for the entire structure. For flat-slab structures,

load-bearing wall structures and other situations where the floor system transfers loads directly to the columns or walls, the LLR shall be computed for, and applied to, the floor in each bay.

- **Recast enhanced local resistance in LRFD format**. The enhanced local resistance requirements retain the same overall approach, in terms of ensuring that the shear resistance is greater than the flexural resistance of columns, but the overall approach has been re-written in the load and resistance factor design (LRFD) format, which significantly clarifies the process.

2.3 Cost of Applying UFC 4-023-03

The cost of implementing progressive collapse design requirements into actual structures was investigated as part of the effort to revise the 2009 UFC 4-023-03. Cost estimates were generated for the four example problems in the appendices of the 2009 UFC 4-023-03.

Appendix D Reinforced Concrete Example. The RC example is a commercial building with a 7-story moment resisting frame that employs Tie Forces and ELR at the corner and penultimate ground floor columns. The plan view of the building is shown in Figure 3. The total floor area is 149,625-ft^2. Baseline costs were estimated for just the structural frame and for the entire building. The baseline costs and the costs with the additional material and labor for the Tie Forces and ELR are summarized in Table 1. The increase for the entire building is 1.38%. Again, the UFC 4-023-03 approach is based on consequences, not risk and consequences; therefore, since it is not possible to determine the reduction in risk, the benefit of this 1.38% expenditure is unknown. Acceptance of this cost and unknown reduction in risk is a policy-level decision that is made by the government or other controlling body.

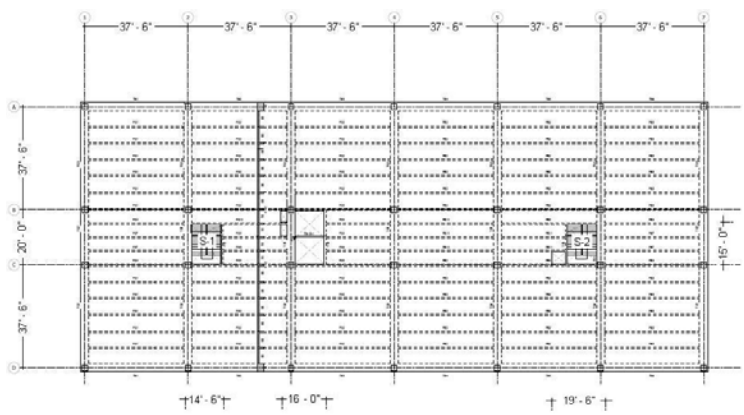

Figure 3. Reinforced Concrete Building from Appendix D, UFC 4-023-03

Table 1. Reinforced Concrete Example Costs

	Baseline Cost	**Baseline plus TF and ELR**	
		Cost	**% Increase**
Structural Frame	$6,796,812	$7,429,580	9.31
Entire Building	$46,348,152	$46,980,919	1.38

Appendix E Structural Steel Example. The steel example is a health care facility with a 4-story moment resisting frame, that employs the Alternate Path method and ELR for the perimeter ground floor columns. The plan view of the building is shown in Figure 4. The total floor area is 86,400-ft^2. Baseline costs were estimated for just the structural frame and for the entire building. Costs were also computed for the application of the linear static and nonlinear dynamic analysis methods for Alternate Path design. Two scenarios were considered: 1. AP is applied to just exterior column removals and 2. AP is applied to both interior and exterior column removals. The results are shown in Table 2. The Linear Static method is deliberately intended to be more conservative than the Nonlinear Dynamic, since Linear Static methods will be less accurate/realistic and thus the associated costs for LS and ND reflect this increase as shown in Table 2.

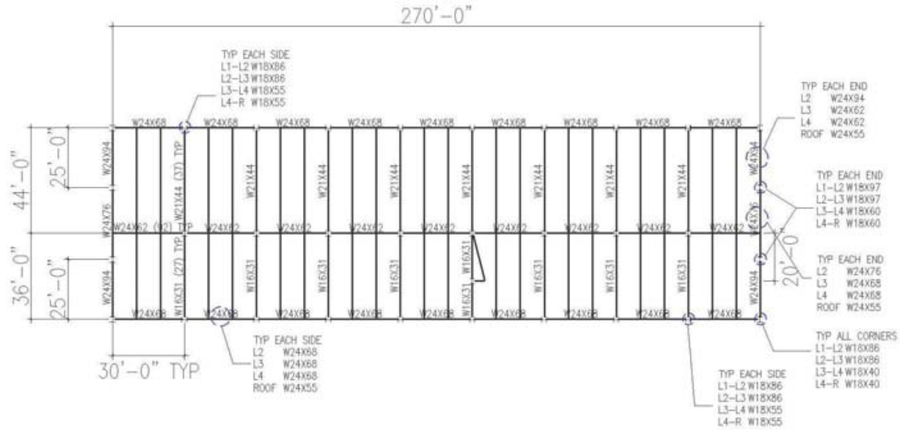

Figure 4. Steel Building from Appendix E, UFC 4-023-03

Table 2. Structural Steel Example Costs

	Baseline Cost	Baseline plus Linear Static AP and ELR Reqm'ts				Baseline plus Nonlinear Dyn. AP and ELR Reqm'ts			
		Ext Col Removal		Ext and Int Col Removal		Ext Col Removal		Ext and Int Col Removal	
		Cost	% Incr.	Cost	% Incr.	Cost	% Incr.	Cost	% Incr.
Structural Frame	$1,541,318	$2,043,315	32.6%	$2,497,415	62.0%	$1,737,671	12.7%	$1,907,959	23.8%
Entire Building	$25,838,943	$26,340,940	1.9%	$26,795,040	3.7%	$26,035,296	0.8%	$26,205,584	1.4%

Appendix F Wood Example. The wood example is a 3-story load-bearing wall barracks that employs the Alternate Path method. The plan view of the building is shown in Figure 5. The total floor area is 19,597-ft^2. Baseline costs were estimated for just the structural frame and for the entire building. The Alternate Path method was applied for different wall removal locations, such as an interior load-bearing wall, exterior load-bearing wall at the 2nd story with and without windows in the removed section, and, exterior load-bearing wall at the 3rd story, at the corner. The costs for implementing the changes due to progressive collapse design requirements are shown in Table 3. The cost to implement the revised 2009 UFC 4-023-03 requirements is small, due to the inherent collapse resistance provided by the deep beam action of the sheathed interior and exterior walls.

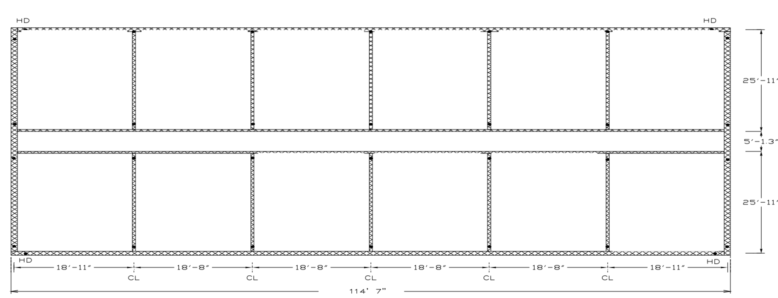

Figure 5. Wood Building from Appendix F, UFC 4-023-03

Table 3. Wood Example Costs

	Baseline Cost	Baseline plus All PC Mods		Baseline plus Interior Wall Removal Mods		Baseline plus Exterior Wall Removal Mods	
		Cost	% Incr.	Cost	% Incr.	Cost	% Incr.
Structural Frame	$623,057	$643,206	3.23%	$624,539	0.24%	$641,724	3.00%
Entire Building	$6,490,981	$6,511,130	0.31%	$6,492,463	0.02%	$6,509,648	0.29%

Appendix G Cold-Formed Steel Example. The cold-formed steel example is a 3-story load-bearing wall barracks that employs the Alternate Path method. The plan view of the building is shown in Figure 6 and is similar to the wood structure. The total floor area is 19,597-ft^2. Baseline costs were estimated for just the structural frame and for the entire building. The Alternate Path method was applied for different wall removal locations, such as an interior load-bearing wall, exterior load-bearing wall, and, exterior load-bearing wall at the 3rd story, at the corner. The costs for implementing the changes due to progressive collapse design requirements are shown in Table 4.

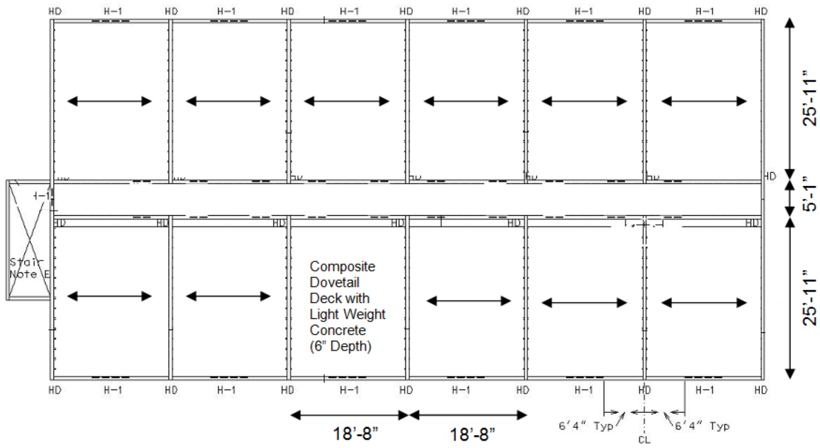

Figure 6. Cold-Formed Steel Building from Appendix G, UFC 4-023-03

Table 4. Cold-formed Steel Example Costs

	Baseline Cost	Baseline plus All PC Mods		Baseline plus Interior Wall Removal Mods		Baseline plus Exterior Wall Removal Mods	
		Cost	% Incr.	Cost	% Incr.	Cost	% Incr.
Structural Frame	$1,708,341	$1,798,017	5.25%	$1,743,880	2.08%	$1,762,478	3.17%
Entire Building	$7,576,265	$7,665,941	1.18%	$7,611,804	0.47%	$7,630,402	0.71%

In summary, the cost to implement the requirements of UFC 4-023-03 is modest when compared to the total cost of a building. However, again, the benefit of reduced risk cannot be calculated and the decision to implement PC design must be based on policy or government mandate.

3. ONGOING PROGRESSIVE COLLAPSE RESEARCH IN NORTH AMERICA

There is a significant level of research into progressive collapse topics ongoing in North America. The following paragraphs highlight some of this work.

The US Defense Threat Reduction Agency (DTRA) and the Singapore Defence Science and Technology Agency (DSTA) have collaborated on an ongoing research program with the overall objectives of understanding the mechanisms of progressive collapse and generating data for validation of high fidelity and engineering models used for analysis of progressive collapse [9]. Two full-scale column removal tests were conducted in 2010 on a four-story reinforced concrete building to measure the structural response and determine if a collapse would occur. The building design incorporated the provisions for structural integrity and prevention of progressive collapse as required by the American Concrete Institute and in the Singapore Code of Practice for Structural Use of Concrete. The structure is shown in Figure 7; more information can be found in Reference [9].

The University of Texas at Austin has teamed with Imperial College, London in a multi-year project sponsored by the US Department of Homeland Security (DHS) [10]. The purpose of the research is to experimentally evaluate the response limits of floor systems commonly found in steel framed structures, as limited research has been conducted to

Figure 7. DTRA/DSTA Full Scale Reinforced Concrete Test Structure

examine floor slab contributions. As mentioned earlier, the 2009 UFC 4-023-03 relies on the ductility and load-carrying capacity of floor slabs to mitigate collapse. Large-scale testing will be carried out on a 2-bay × 2-bay section of a steel framed structure that utilizes composite floor slabs that are consistent with typical building practices in the US; see Figure 8. The tests are designed to evaluate the large-deformation response of the test structure following the removal of an interior or a perimeter column. The experimental research program will be complemented by detailed computational analyses.

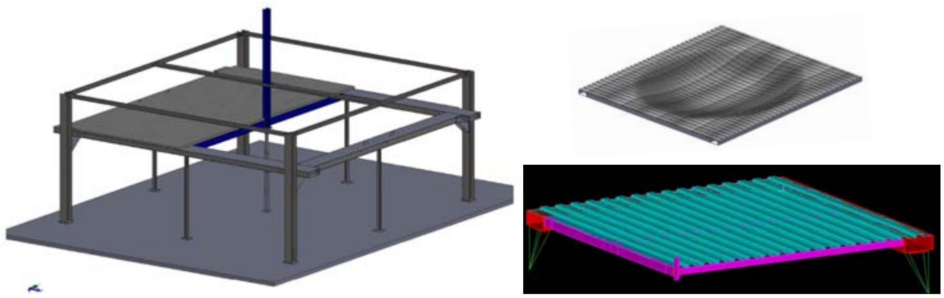

Figure 8. UT-Austin Large-Scale Test Structure with Numerical Models

The US National Institute of Standards and Technology (NIST) has an active research program into progressive collapse [11]. Recent work includes experimental and numerical investigations of key structural components within steel and reinforced concrete buildings; see Figure 9. NIST and Hunan University are working jointly to investigate several different sudden column removal scenarios for a half-scale RC building. The structural design and test plan was developed by NIST, who also conducted pre-test predictions.

A collaborative research project supported by the American Institute of Steel Construction (AISC) and the National Science Foundation (NSF) is underway at the University of Washington, Purdue University and the University of Illinois at Urbana-Champaign to investigate the structural integrity of steel gravity frame systems [12]. The research program includes experiments of steel connections and composite concrete slab on metal deck, and also the behavior of complete steel gravity frame systems; see Figure 10.

Researchers at the University of Alberta are studying the performance of steel shear connections under combined moment, shear and tension; see Figure 11 [13]. Full-scale physical tests have been performed to investigate the behavior of common steel shear connections under load histories emulating the anticipated effects of the loss of an adjacent column, including large rotations and the development of axial tension. Tests have included shear tab, single angle and double angle specimens.

Figure 9. Examples of NIST Progressive Collapse Research

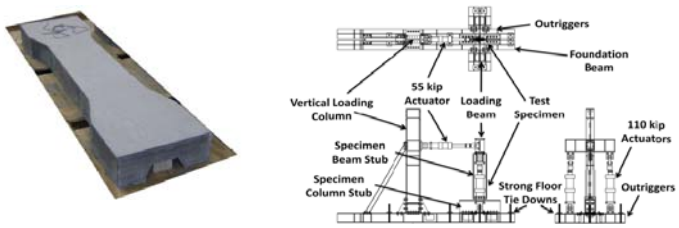

Figure 10. NSF/AISC Test Specimens and Fixture

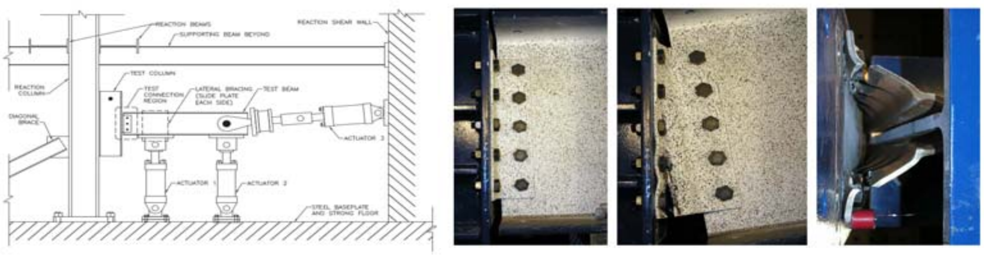

Figure 11. University of Alberta Test Device and Specimen

Researchers at the University of Michigan are investigating the role that flexural composite action between the concrete deck and underlying steel beams plays in the collapse resistance of steel structures [14]. A 10-story, seismically designed steel building is used as a case study. The results show that slab-beam flexural composite action contributes significantly in the initial stages of collapse response, by reducing deformation levels.

Researchers at Georgia Institute of Technology have applied energy-based nonlinear static pushdown analyses to meet the need for a relatively simple procedure for preliminary vulnerability assessment of regular building frames subjected to local damage [15].

4. APPLICATIONS OF STRUCTURAL DESIGN SOFTWARE TOOLS TO PROGRESSIVE COLLAPSE

There are a number of structural design software tools available to the general public; these include SAP2000, ETABS, etc. Many of these codes are designed to perform seismic design and have implemented the general procedures outlined in ASCE 41. Geometric and material nonlinear response of structures subjected to dynamic loads can be modeled; however, the inclusion of catenary mechanisms can be challenging. These codes are intended to be used by practicing structural engineers as design tools and as such do not have the complexity or nuances associated with HFPB numerical analysis codes such as LS-DYNA.

This “simplicity” can actually be an advantage of design-type codes such as SAP2000, ETABS, etc, when compared to HFPB codes. The quality of HFPB predictions depend heavily upon the experience of the modeler and can vary significantly from building to building. Much of the uncertainty associated with HFPB models such as LS-DYNA is due to the application of material models for concrete which can be inaccurate in regimes where high shear stress is combined with one principle stress that is tensile, as typically occurs at beam-column joints; another limitation is the de-stabilizing effect of strain-softening and the associated mesh dependency. Predictions from such HFPB codes should be viewed with skepticism until test data are available for validation.

While SAP2000 is not an analysis tool, per se, it can be used to assess building performance under progressive collapse-type scenarios. PEC is currently developing and assessing SAP2000 models that employ the modeling procedures in the 2009 UFC 4-023-03; these models are and will be used to evaluate full-scale structures subjected to collapse conditions. The initial model results appear promising but more work is needed to assess the ability of SAP2000 to model the large displacements and catenary behavior. The comparison of results from a nonlinear “stick and hinge” model that includes only beams and columns and from a model with beams, columns, and nonlinear shell elements for the floor slab clearly show that the floor system contributes greatly to resisting collapse and should not be ignored for such structures. Additional results will be obtained and reported as the effort progresses.

5. Conclusions

There are many interesting and important topics within the area of progressive collapse phenomenology and there is much work to be done. A significant amount of progressive collapse research and code improvement is currently being performed in North America, as discussed herein. This work will steer and shape the development of future progressive collapse design requirements and procedures. It is hoped that such efforts can be coordinated with the international community, for the benefit of all.

Acknowledgements

The ongoing support of the US DoD for research and development in progressive collapse design, analysis, and testing is acknowledged.

References

[1] Department of Defense (DoD). *Interim Antiterrorism/Force Protection Construction Standards - Progressive Collapse Design Guidance*, Department of Defense, Washington, DC, 2001.
[2] DoD. *Design of Buildings to Resist Progressive Collapse, UFC 4-023-03*, Department of Defense, Washington, DC, 2005.
[3] DoD, *Design of Buildings to Resist Progressive Collapse, UFC 4-023-03*, Department of Defense, Washington, DC, 2009.
[4] Ministry of Housing and Local Government, *Report of the Inquiry into the Collapse of Flats at Ronan Point*, Canning Town. HM Stationery Office, London, 1968.
[5] British Standards, *BS EN 1991-1-7, Actions on structures - Part 1-7: General actions - Accidental Actions*, British Standards Institution, London, England, 2006
[6] Stevens, D., *Assessment and Proposed Approach for Tie Forces in Framed and Load-bearing Wall Structures*, Project Report, Protection Engineering Consultants, San Antonio, Texas, Original May 2008; Revised March 2012
[7] American Society of Civil Engineer (ASCE), *Seismic Rehabilitation of Existing Buildings*, ASCE 41-06, Reston, Virginia, 2006.
[8] DoD, *Minimum Antiterrorism Standards for Buildings, UFC 4-010-01*, Department of Defense, Washington, DC, 2012.
[9] Sheffield, C., Kersul, A., Hoon, V., and Amini, A., *An Instrumented Full-Scale Building Progressive Collapse Test*, Proc. of 14th International Symposium on Interaction of the Effects of Munitions with Structures, Seattle, Washington, 2011.
[10] Donahue, S., Hadjioannou, M., Williamson, E., Engelhardt, M., Izzuddin, B., Nethercot, D., Zolghadrzadehjahromi, H., Stevens, D., Marchand, K., and Waggoner, M., *Experimental Evaluation of Floor Slab Contributions in Mitigating Progressive Collapse of Steel Structures*, Proc. of 14th International Symposium on Interaction of the Effects of Munitions with Structures, Seattle, Washington, 2011.
[11] National Institute of Science and Technology (NIST), *An Experimental and Computational Study of Reinforced Concrete Assemblies under a Column Removal Scenario*, NIST Technical Note 1720, US Department of Commerce, Washington, DC .
[12] Weigand, J., Meissner, J., Francisco, T., Berman, J., Fahnestock, L., and Liu, J., *Overview of AISC/NSF Structural Integrity Research and Preliminary Results*, Proc. of the 2012 Structures Congress, Chicago, Illinois, 2012.
[13] Oosterhof, S., and Driver, R., *Performance of Steel Shear Connections under Combined Moment, Shear, and Tension*, Proc. 2012 Structures Congress, Chicago, Illinois, 2012.
[14] Li, H., and El-Tawil, S., *Role of Composite Action in Collapse Resistance of Steel Frame Buildings*, Proc. of the 2012 Structures Congress, Chicago, Illinois, 2012.
[15] Xu, G., and Ellingwood, B, *An Energy-based Partial Pushdown Analysis for Robustness*, Proc. of the 2012 Structures Congress, Chicago, Illinois, 2012.