Elegant Resistance: The Art and Engineering of Collapse-Resistant Masonry

TMS Annual Meeting – Session #1A
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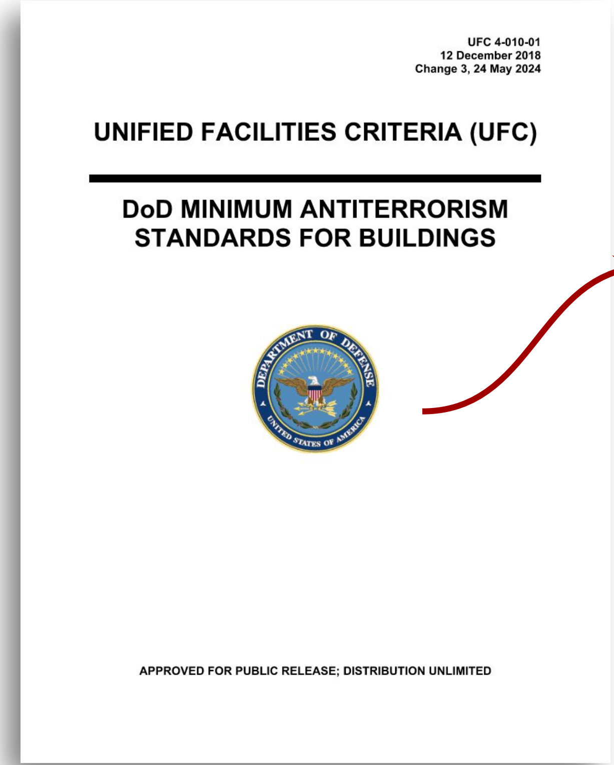
UFC Requirements

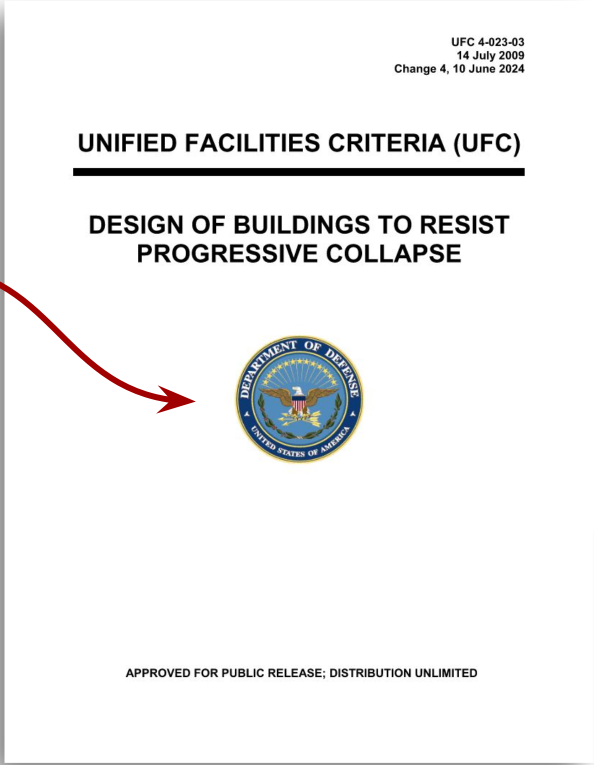

UFC 4-010-01
12 December 2018
Change 3, 24 May 2024

UNIFIED FACILITIES CRITERIA (UFC)

DoD MINIMUM ANTITERRORISM STANDARDS FOR BUILDINGS

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

Standard 1 - Standoff Distance
Standard 2 - Unobstructed Space
Standard 3 - Drive-up/Drop-Off Areas
Standard 4 - Access Roads
Standard 5 - Parking Beneath Buildings
Standard 6 - Progressive Collapse Resistance
Standard 7 - Structural Isolation
Standard 8 - Building Overhangs and Breezeways
Standard 9 - Exterior Masonry Walls
Standard 10 - Glazing
Standard 11 - Building Entrance Layout
Standard 12 - Exterior Doors
Standard 13 - Mail Rooms and Loading Docks
Standard 14 - Roof Access
Standard 15 - Overhead Mounted Architectural Features
Standard 16 - Air Intakes
Standard 17 - Mail Room and Loading Dock Ventilation
Standard 18 - Emergency Air Distribution Shutoff
Standard 19 - Equipment Bracing
Standard 20 - Under Building Access
Standard 21 - Mass Notification


UFC 4-023-03
14 July 2009
Change 4, 10 June 2024

UNIFIED FACILITIES CRITERIA (UFC)

DESIGN OF BUILDINGS TO RESIST PROGRESSIVE COLLAPSE

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Image Credits: U.S. Department of Defense. UFC 4-010-01: DoD Minimum Antiterrorism Standards for Buildings. Washington, D.C.: U.S. Government, 2024.

Designing Masonry for Progressive Collapse

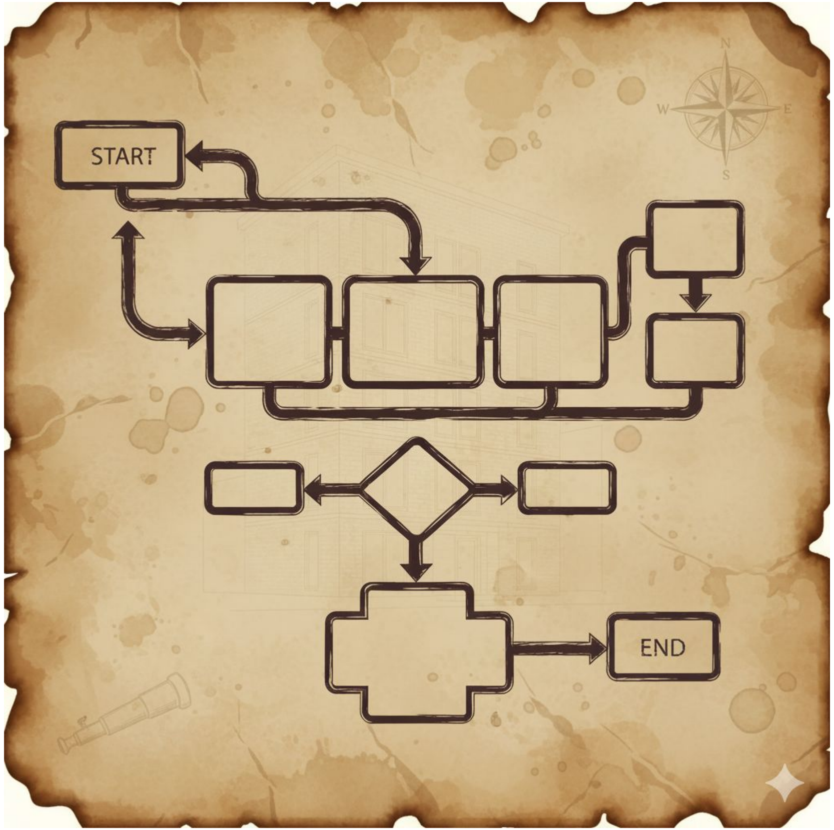

Image Credits: Google. (2025, October 5). *Image of an old treasure map process flowchart* [AI-generated image]. Gemini. https://gemini.google.com/

30 years after the Oklahoma City bombing

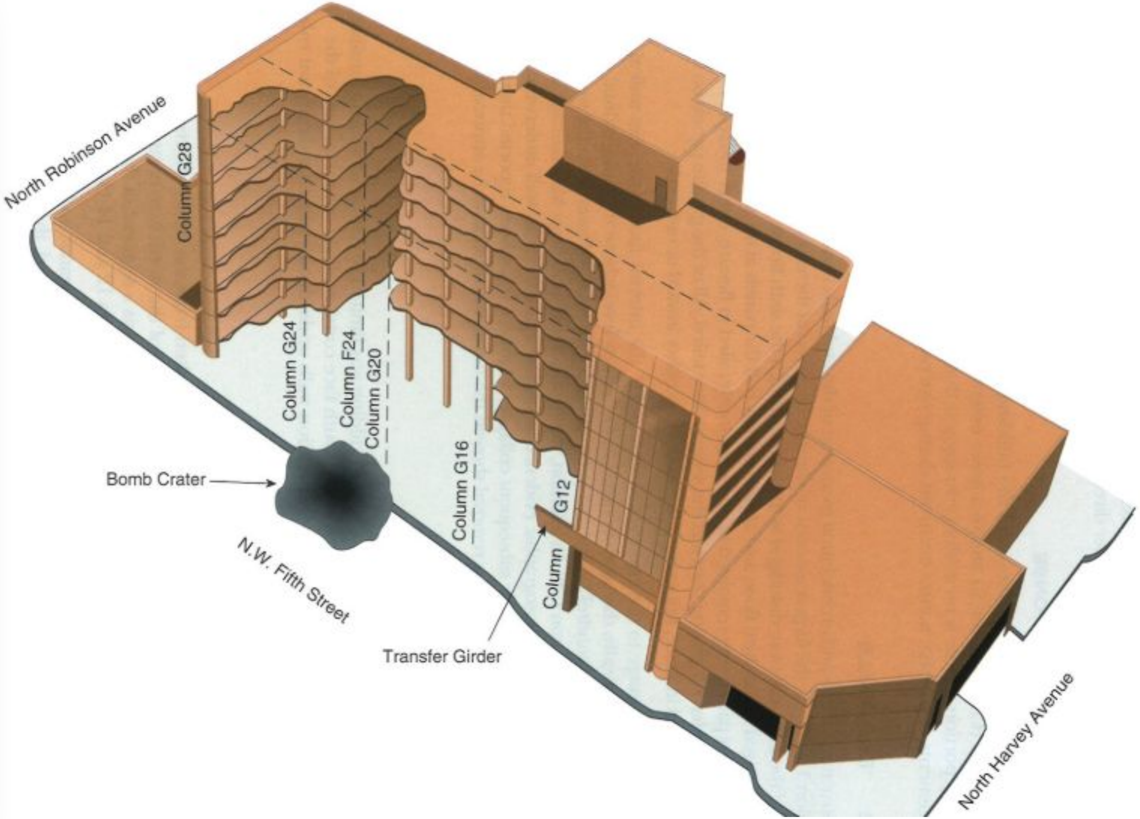

Image Credits: https://memorialmuseum.com/museum/about-us/ and FEMA 277. "*The Oklahoma City Bombing: Improving Building Performance through Multi-Hazard Mitigation"*

Blast Design vs. Progressive Collapse

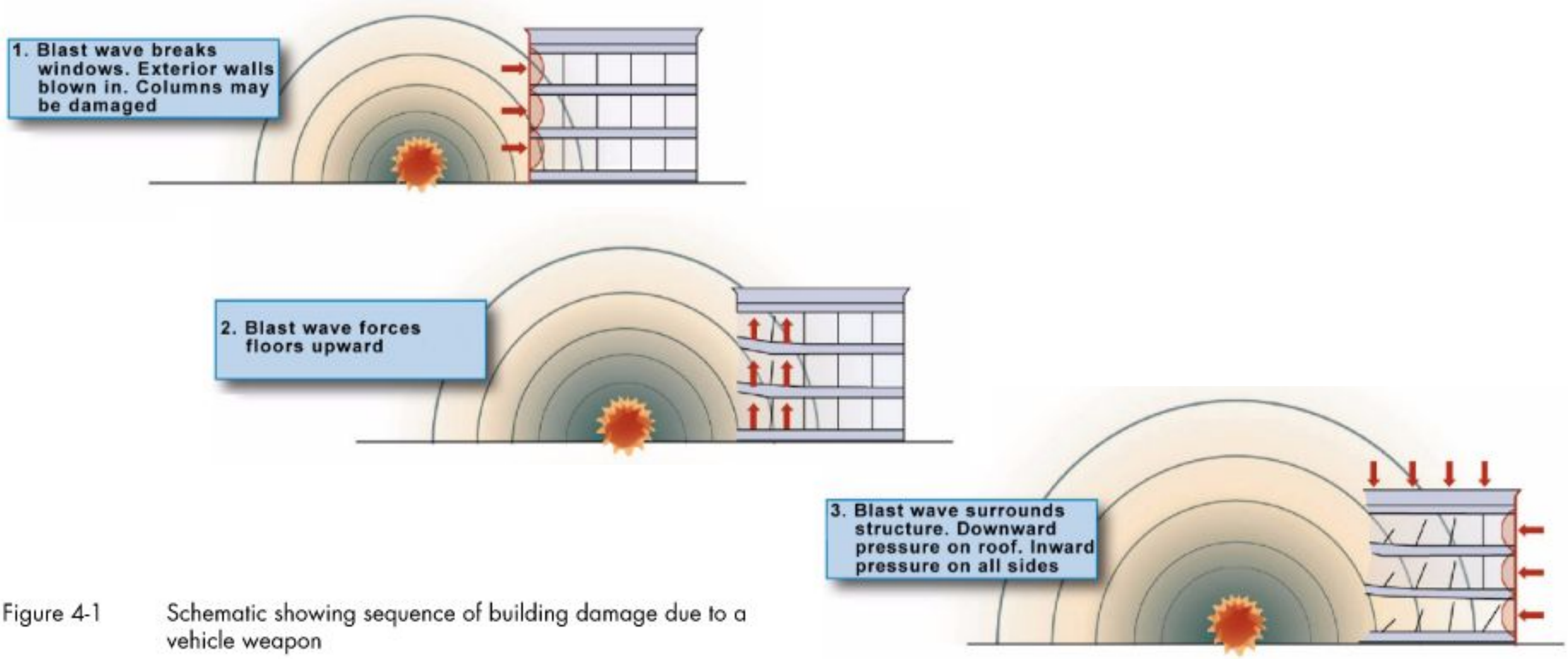

Figure 4-1 Schematic showing sequence of building damage due to a vehicle weapon

Image Credits: United States Federal Emergency Management Agency. (2003). Primer for design of commercial buildings to mitigate terrorist attacks (FEMA 427).

Blast Design vs. Progressive Collapse

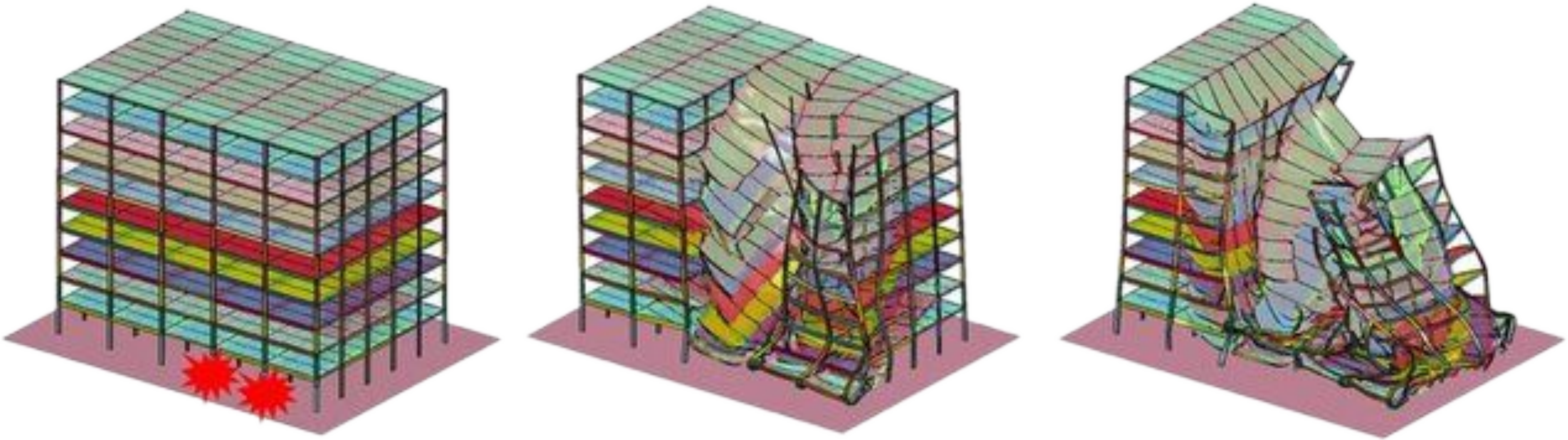

Image Credits: Njugi, Rhonnie. (2018). Progressive Collapse Analysis of Steel Framed Buildings - With Robot Structural Analysis; Google. (2025, October 5). Image of dominoes falling

Learning Objectives

- Describe the current state of the art for progressive collapse design and detailing.
- Explain UFC 4-023-01 requirements for progressive collapse resistance specific to masonry construction.
- Evaluate reinforced masonry detailing for progressive collapse resistance.

Progressive Collapse Design Approaches

- Tie Force Approach (TF)
  - Limited building geometry
  - Provide strategic tension ties (vertical, longitudinal, transverse, peripheral)

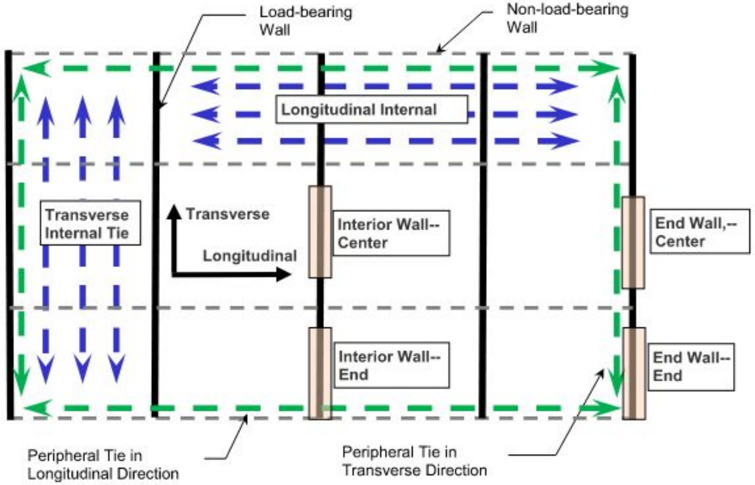

Figure C-3. Plan View of One-way Load-bearing Wall Structure

Figure 3-1. Tie Forces in a Frame Structure

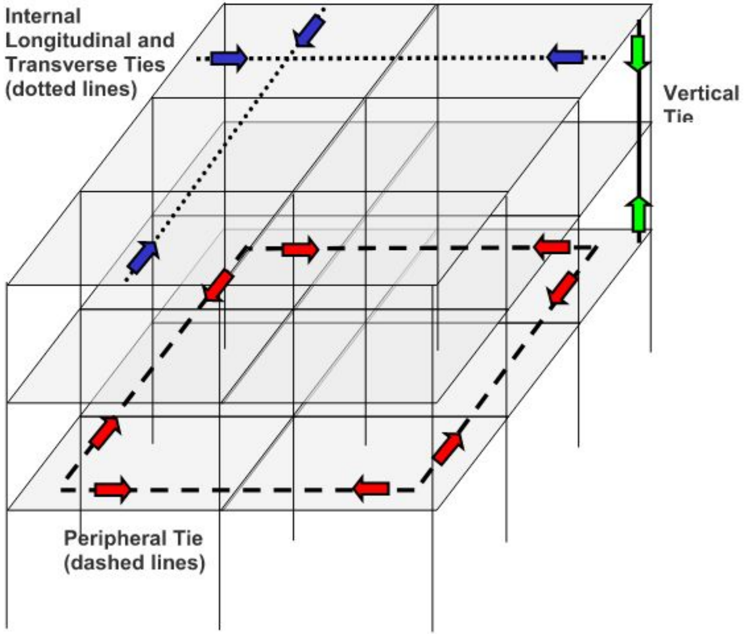

Image Credits: U.S. Department of Defense. UFC 4-023-03: Design of Buildings to Resist Progressive Collapse. Washington, D.C.: U.S. Government, 2024.

Progressive Collapse Design Approaches

- Alternate Path Method (AP)
  - Required for buildings with irregularities
  - Systematically remove load bearing elements
  - Directly design for load redistribution with elements removed
  - Works well for bearing wall structures

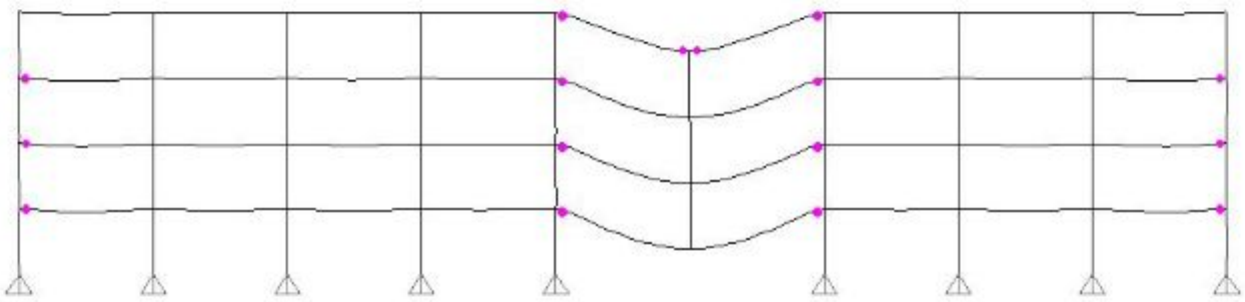

Figure E-20. Column 1 Removal Convergence After Redesign

Image Credits: U.S. Department of Defense. UFC 4-023-03: Design of Buildings to Resist Progressive Collapse. Washington, D.C.: U.S. Government, 2024.

Progressive Collapse Design Approaches

- Enhanced Local Resistance (ELR)
  - Local hardening
  - Design for shear strengths that exceed the shear demand associated with the flexural demands of the columns
  - Design connections for rebound

- Component Demand-Capacity checks using Linear Static Procedure:

$$\phi\, m\, Q_{CE} \geq Q_{UD} \text{ deformation-controlled actions}$$
$$\phi\, Q_{CL} \geq Q_{UF} \text{ force-controlled actions}$$

- Ultimate (factored) loading; actual expected material strengths

Image Credits: U.S. Department of Defense. UFC 4-023-03: Design of Buildings to Resist Progressive Collapse. Washington, D.C.: U.S. Government, 2024.

Progressive Collapse Design Resources for Masonry – What's Available?

- Many references available for other materials, but what about Masonry?
- United Facilities Criteria (UFC) 4-023-03 *Design of Buildings to Resist Progressive Collapse*, Change 4, dated 10 June, 2024.
- Erdogmus, Ece & Kousgaard, Ariel. (2015). *State-of-the-Art Review on the Resilience of Existing Masonry Wall Buildings against Progressive Collapse.*
- NISTIR 7396, *Best Practices for Reducing the Potential for Progressive Collapse in Buildings*, February, 2007.
- Li, Kai., *Collapse Experiments and Assessment of Masonry Wall Buildings*, Ph.D., Civil Engineering, Ohio State University, 2017.

What About Masonry?

- Expanded code and commentary for Steel and Reinforced Concrete
- Guidance is limited for Masonry, Wood, and Cold-Formed Steel
- Directs to ASCE 41 for Modeling and Acceptance Criteria

CHAPTER 6 MASONRY

This chapter provides the specific requirements for designing a masonry building to resist progressive collapse.

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6-4 ALTERNATE PATH METHOD FOR MASONRY.

6-4.1 General.

Use the Alternate Path method in Section 3-2, where applicable, to verify that the structure can bridge over removed elements.

6-4.2 Modeling and Acceptance Criteria for Masonry.

Use the modeling parameters, nonlinear acceptance criteria and linear m-factors for the Life Safety condition from Chapter 11 of ASCE 41 for primary and secondary components. Use the modeling parameters and guidance, including definitions of stiffness, to create the analytical model.

. . .

6-5 ENHANCED LOCAL RESISTANCE REQUIREMENTS FOR MASONRY.

Apply the Enhanced Local Resistance requirements in Section 3-3, where applicable, for framed and load-bearing wall masonry buildings.

What About Masonry?

Figure B-7. Story Drift

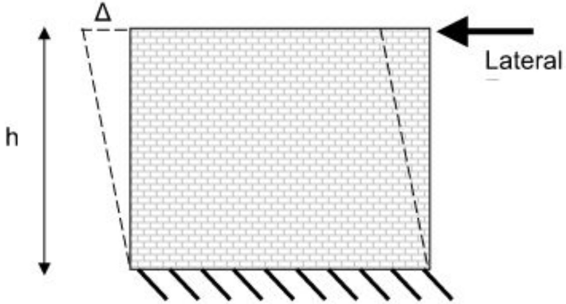
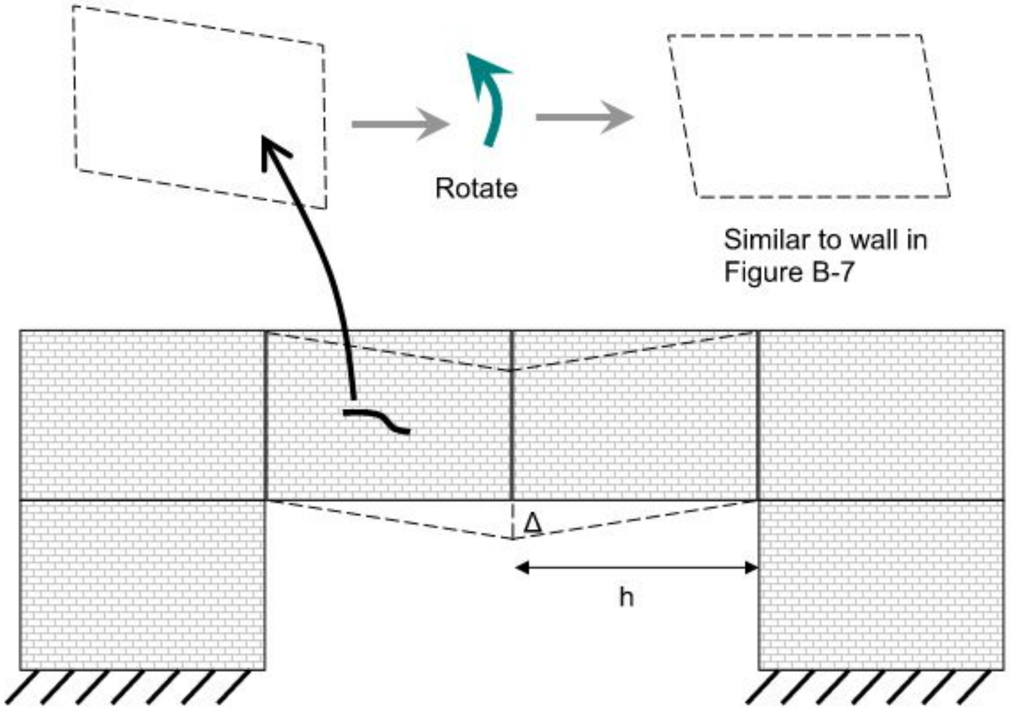


Figure B-8. Vertical Wall Deflection (Drift)



Appendix B-3 *Definitions for Structural Analysis Procedures*

"Story Drift"

Image Credits: U.S. Department of Defense. UFC 4-023-03: Design of Buildings to Resist Progressive Collapse. Washington, D.C.: U.S. Government, 2024.

What About Masonry?

- Appendices contain worked examples for:
  - Reinforced Concrete
  - Structural Steel
  - Wood
  - Cold-Formed Steel

- **No Masonry Examples!**

APPENDIX D REINFORCED CONCRETE EXAMPLE
- D-1 INTRODUCTION.
- D-2 BASELINE PRELIMINARY DESIGN.
- D-3 \2\TIE FORCE DESIGN.

APPENDIX E STRUCTURAL STEEL EXAMPLE
- E-1 INTRODUCTION.
- E-2 BASELINE PRELIMINARY DESIGN.
- E-3 LINEAR STATIC PROCEDURE.
- E-4 NON LINEAR DYNAMIC PROCEDURE (NDP).
- E-5 RESULTS COMPARISON.

APPENDIX F WOOD EXAMPLE
- F-1 INTRODUCTION
- F-2 BASELINE DESIGN
- F-3 ALTERNATE PATH ANALYSIS

APPENDIX G COLD FORMED STEEL EXAMPLE
- G-1 INTRODUCTION
- G-2 BASELINE DESIGN
- G-3 ALTERNATE PATH ANALYSIS

What About Masonry?

- What is the "effective height" that must be removed?

"For both external and internal column removal, for the purposes of AP analysis, **beam-to-beam continuity is assumed to be maintained** *across a removed column; see Figure 3-8."*

Figure 3-8. Removal of Column from Alternate Path Model

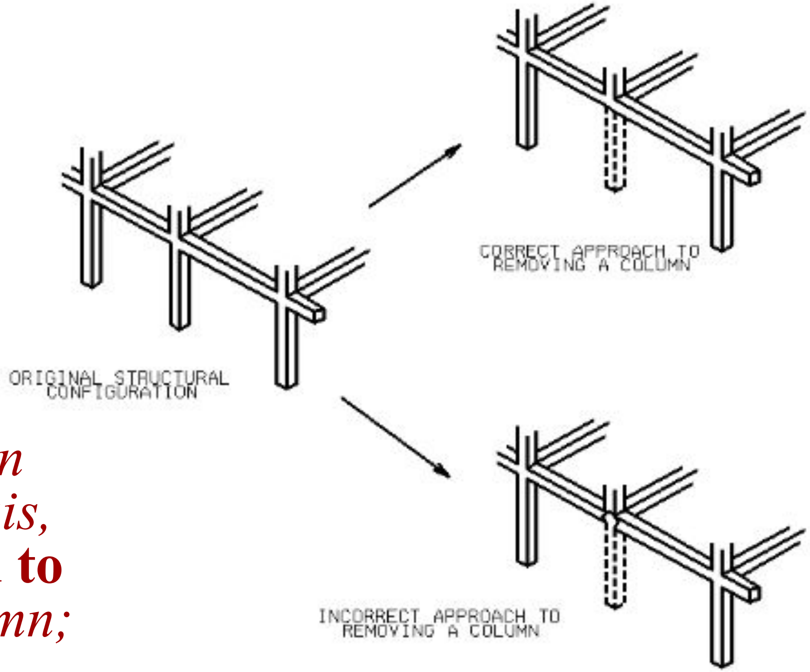


Image Credits: U.S. Department of Defense. UFC 4-023-03: Design of Buildings to Resist Progressive Collapse. Washington, D.C.: U.S. Government, 2024.

ASCE 41 Applicability

- Developed for seismic evaluation and retrofit of existing masonry
- Detailed information on unreinforced masonry; less available for reinforced masonry
- Addresses In-Plane (horizontal) and Out-of-Plane behavior only
- Material Strengths
  - Expected Strengths of materials (steel and masonry versus specified strengths)
  - Uncracked sections for shear stiffness
  - Cracked sections for flexure (50% Ig)

- **No Arching Action!**

ASCE 41 m-Factors

Table 11-6. Acceptance Criteria for Linear Procedures—Reinforced Masonry In-Plane Walls

			m-Factors[a]				
			Performance Level				
				Component Type			
				Primary		Secondary	
f_{ae}/f_{me}	h_{eff}/L	$\rho_g f_{ye}/f_{me}$[b]	IO	LS	CP	LS	CP
Wall Components Controlled by Flexure							
0.00	≥2.0	≤0.01	4.0	7.0	8.0	8.0	10.0
		0.05	2.5	5.0	6.5	8.0	10.0
		≥0.20	1.5	2.0	2.5	4.0	5.0
			. . .				
Wall Components Controlled by Shear							
All cases[c]	All cases[c]	All cases[c]	2.0	2.0	3.0	2.0	3.0

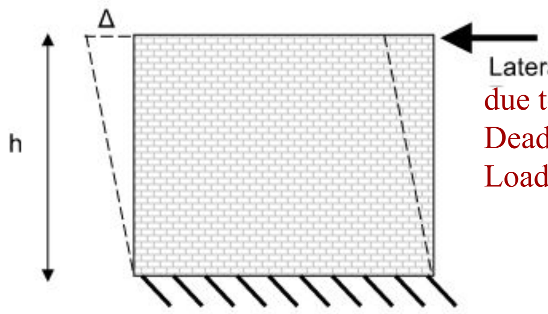
[a] Interpolation shall be used between table values.
[b] $\rho_g = \rho_v + \rho_h$.
[c] For wall components governed by shear, the axial stress f_{ae} on the member must be less than or equal to $0.15f'_m$; otherwise, the component shall be treated as force controlled.

Solution Strategies Considered

- Sideways Dual Cantilevered Wall Analogy
- Deep Beam Approach
- Strut and Tie Method
- Finite Element Modeling

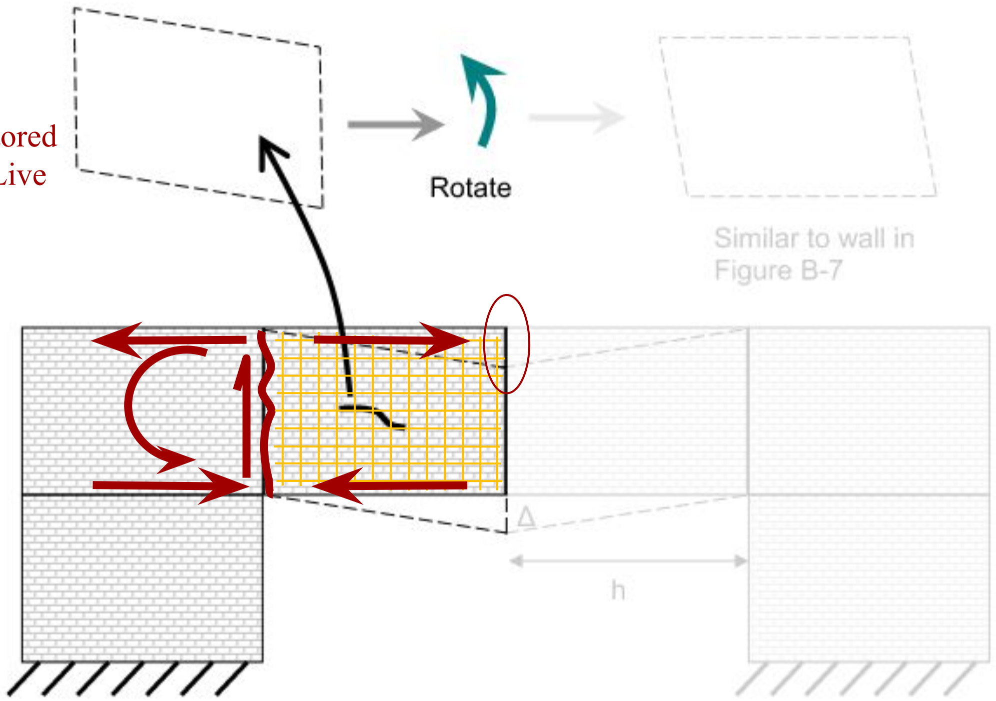
Sideways Dual Cantilevered Wall Analogy

Figure B-7. Story Drift



due to Factored Dead and Live Loads

Figure B-8. Vertical Wall Deflection (Drift)



No arching or deformation compatibility in compression zone

BUT

Shear friction & distributed reinforcement concept

Image Credits: U.S. Department of Defense. UFC 4-023-03: Design of Buildings to Resist Progressive Collapse. Washington, D.C.: ~~U.S. Government, 2024~~.

How masonry walls actually deflect after removals:

Figure 4.29: Four removed walls and LVDT numbering and locations

Figure 4.31: Nosker House after the removal of four walls

Floor to Floor height: 9’-6”

Removal order: A→B→C→D

Image Credits: Li, Kai., Collapse Experiments and Assessment of Masonry Wall Buildings, Ph.D., Civil Engineering, Ohio State University, 2017.

How masonry walls actually deflect after removals:

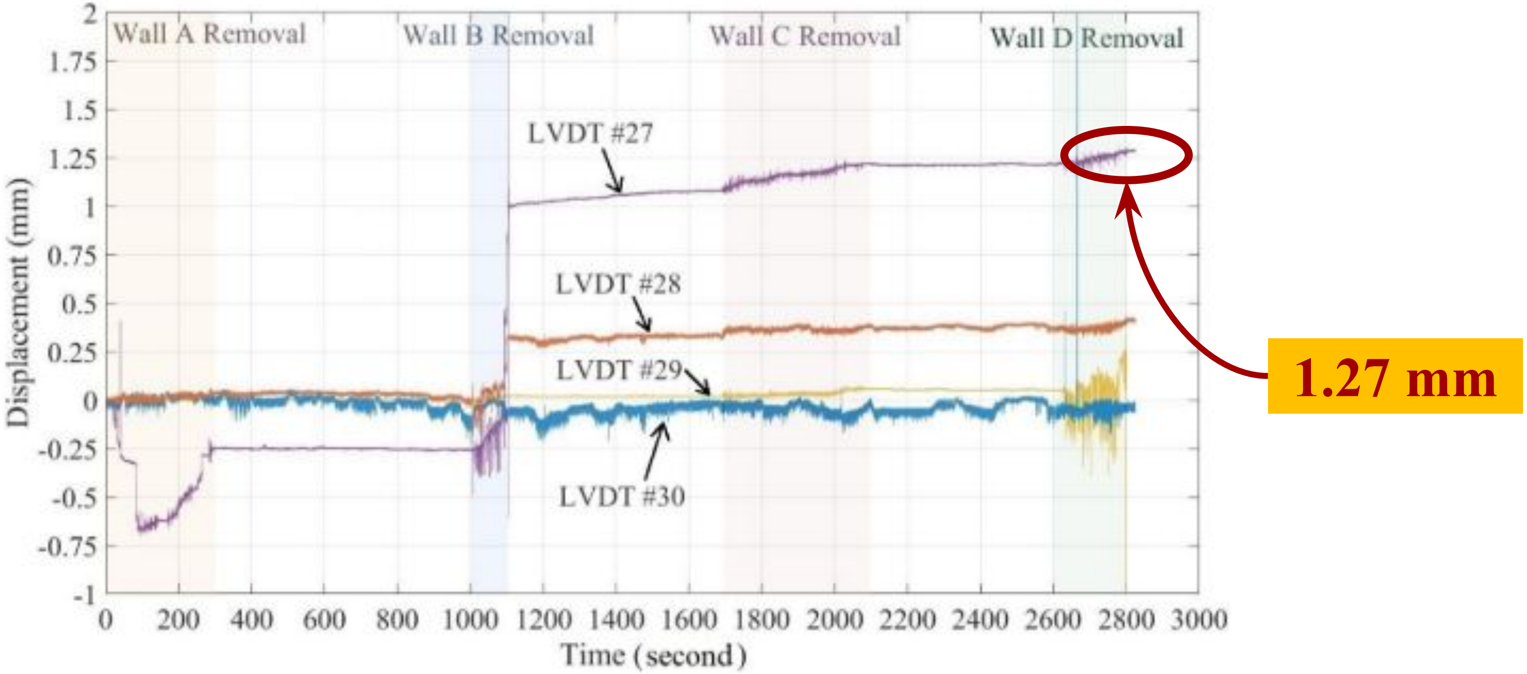


Figure 5.9: LVDT data plot of Nosker House field experiment

Image Credits: Li, Kai., Collapse Experiments and Assessment of Masonry Wall Buildings, Ph.D., Civil Engineering, Ohio State University, 2017.

Experimental Building Typical Wall Section

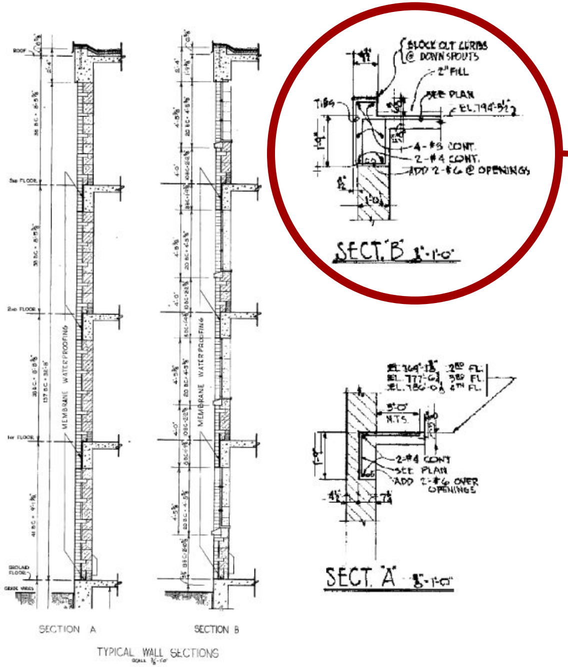


Figure 4.4: Typical wall sections (left) and typical edge beam sections of roof floor (top right drawing) and other floors (right bottom drawing)

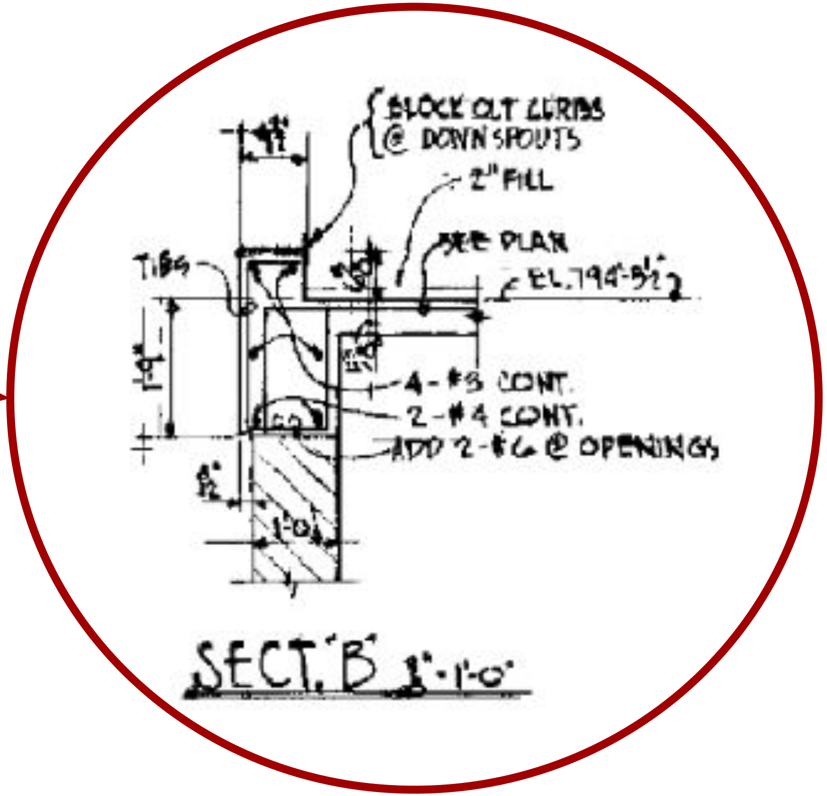


Image Credits: Li, Kai., Collapse Experiments and Assessment of Masonry Wall Buildings, Ph.D., Civil Engineering, Ohio State University, 2017.

Deep Beam Approach

5.3.2.2 *Internal Lever Arm* — Unless determined by a more ***comprehensive analysis***, the internal lever arm, *z*, shall be taken as the value in Table 5.3.2.2, based on the span condition and ratio of $\ell eff / dv$.

Table 5.3.2.2: Internal Lever Arm

Span Condition	Ratio	Internal Lever Arm (z)
Simply Supported	$1 \leq \ell_{eff} / d_v < 2$	$0.2(\ell_{eff} + 2d_v)$
	$\ell_{eff} / d_v < 1$	$0.6\ell_{eff}$
Continuous	$1 \leq \ell_{eff} / d_v < 3$	$0.2(\ell_{eff} + 1.5d_v)$
	$\ell_{eff} / d_v < 1$	$0.5\ell_{eff}$

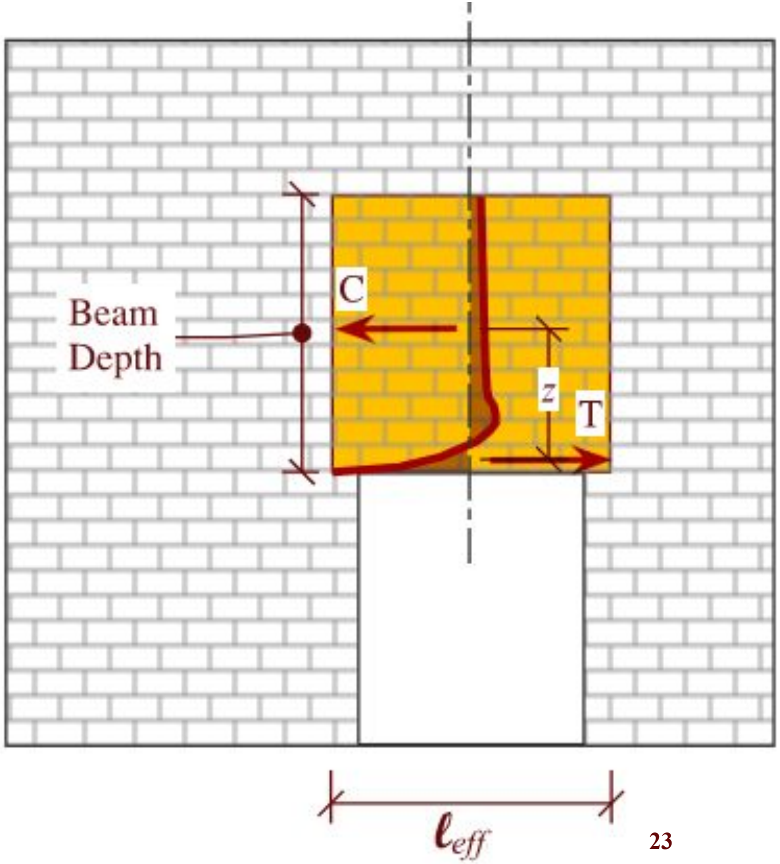


Image Credits: Adapted from Figure CC-5.3-2 of TMS 402/602-22 Building Code Requirements for Masonry Structures; Specification for Masonry Structures.

Strut & Tie Method

- Following the approach outlined in ACI 318 Chapter 23, substituting f'_m for f'_c and 0.80 for 0.85 β_n:

$$F_{nn} = \beta_n f_m A_{nz}$$

$$F_{ns} = \beta_s f_m A_{cs} + A'_s f'_s$$

$$w_t = \frac{A_{ts} f_y}{\beta_n f_m b_s}$$

$$F_{nt} = A_{ts} f_y$$

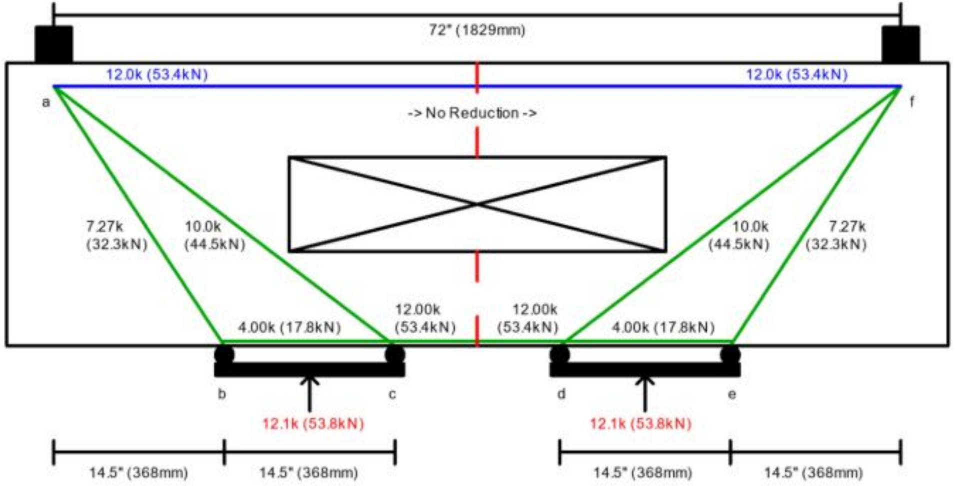


Fig. 14. Beam 1-1-UO strut-and-tie model.

Image Credits: Ring, J. D., & Jennifer E. Tanner. "Evaluation of Masonry Beams with Openings and Validation Using a Strut-and-Tie Model." Journal of Structural Engineering 147, no. 12 (2021)

Strut & Tie Method

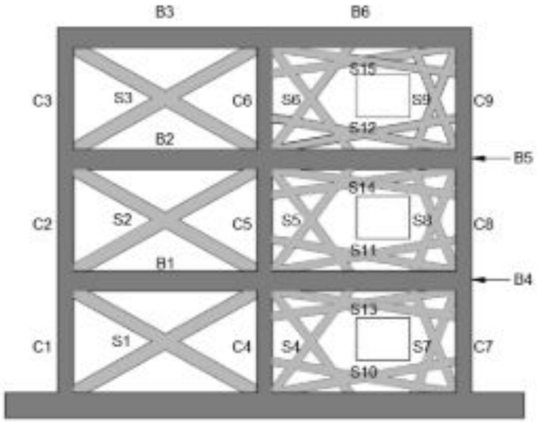


Figure 8: Identification of the different members.

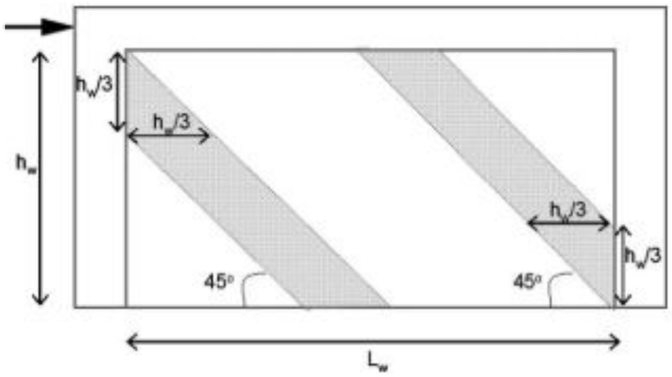


Figure C11-11. Compression Strut Analogy—Struts at 45 Degrees Acting at the Top of the Left (Windward) Column and the Bottom of the Right (Leeward) Column
Source: Stavridis (2009); reproduced with permission.

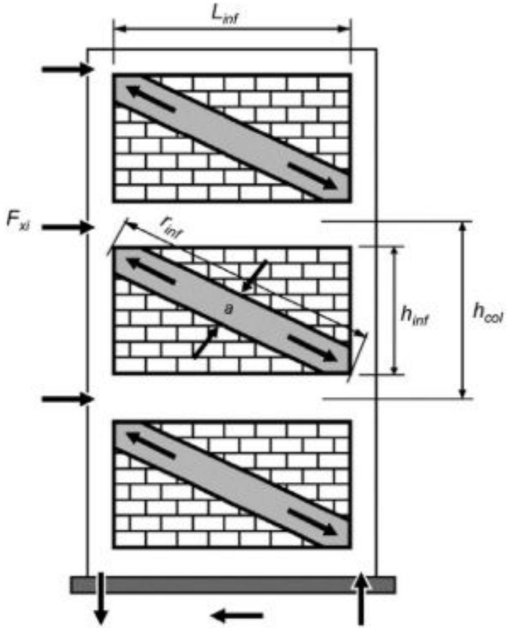


Figure C11-9. Compression Strut Analogy—Concentric Struts

Image Credits: Stavridis, Andreas, J. Martin, and S. Bose. "Updating the ASCE 41 provisions for infilled RC frames." In Proceedings of the 2017 SEAOC Convention, San Diego, California. 2017; ASCE 41-17

Finite Element Analysis

- RISA 3D
  - Started with RISA Floor, only to discover that wall panel elements cannot be exploded for manual node/mesh refinement or removals
- Plate elements for CMU walls, beam elements for primary steel beams
- No secondary beams modeled
- No diaphragms modeled
- Pilasters modeled as a "T" with interior plates perpendicular to exterior wall

FEA Modeling Assumptions

- E_m reduced by 50% to approximate cracking (EI_{eff})
- Dummy beams with near zero cross-section and masonry material assignment for faster line load modeling (irrespective of node spacing)
  - Brick relief elevations
  - Windows
  - Slabs
- Eccentric gravity loads imparted by slabs and beams modeled as point and distributed moments
- Used worst case m-Factor for all masonry to establish the required factored load combinations

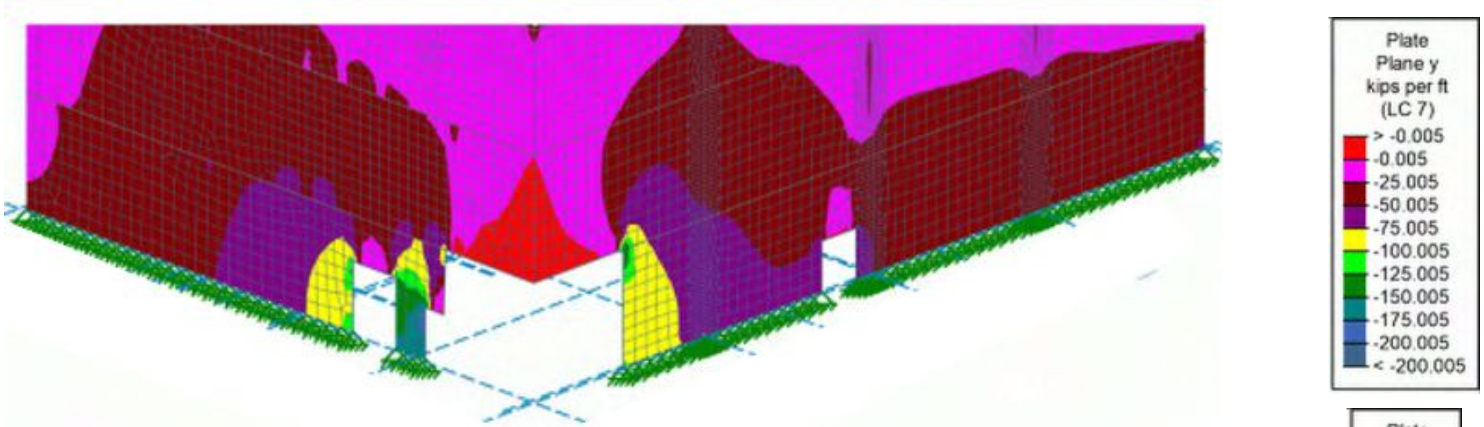
FEA Model Results Interpretation

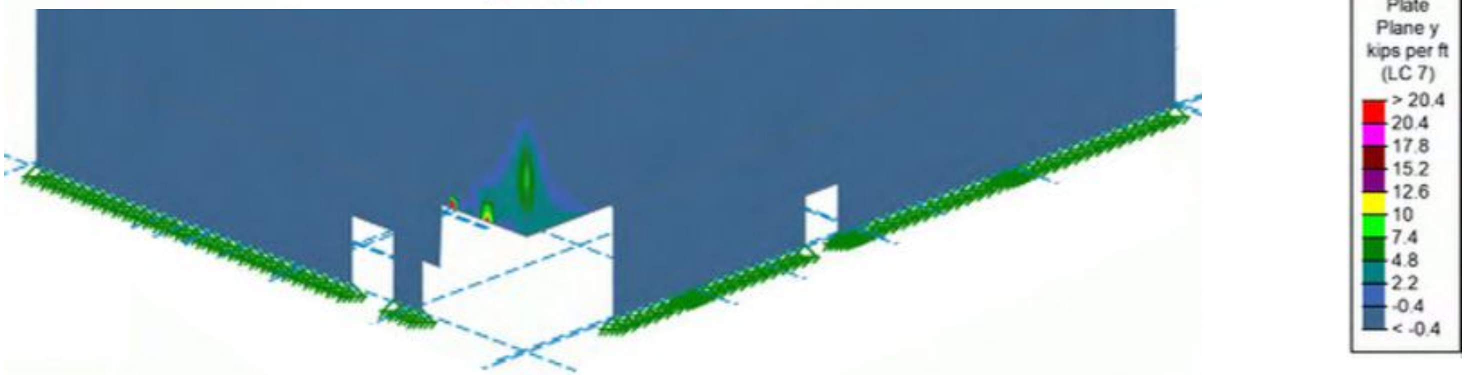
- Quantitative and Qualitative Model Validation
  - Compared hand-calculated load takedowns to applied loads
    - Revealed modeling errors stemming from transition from RISA Floor to RISA 3D (gravity loads were lost)
    - Revealed unit errors in applied moments vs. program default units
  - Deflected shape analysis
    - Revealed submeshing errors with adjacent nodes not being coincident
    - Confirmed pilaster double curvature due to load eccentricity
  - Plate contours review (Fx, Fy, Fxy, Mx, My, and Mxy)
    - Revealed that dummy members initially drawn were too stiff/preventing arching action - once corrected, tension developed where expected

FEA Model Results Interpretation

- Inactivated selected plates from model and ran analysis for each required removal
- Reviewed overall displacements
- Hand calculated capacity envelope:
    - ϕTn for baseline prescriptive steel in terms of k/ft
    - Strong and Weak axis interaction diagram for pilasters
    - ϕRn for bearing at corners of removal kips
    - ϕTn for beam saddles in kips
    - ϕPn for wall segment in compression for various values of "h"
    - ϕFf for shear friction (without gravity precompression benefit) in k/ft
- Graphically reviewed contours for patterns and stress concentrations; used force summation and spreadsheet tools to calculate demands
- Filtered contours to highlight compression (negative) versus tension (positive)

FEA Model Results Interpretation





Detailing – General

- Solid grouted CMU at exterior
- #5@8” o.c. horizontally and vertically, minimum (prescriptive)
- (2) bars in bond beams
- Additional bond beams as required at discontinuities (windows, openings)
- Vertical tie reinforcement as required at corners with discontinuities (stair towers with windows)
- Parapet with bond beams used to develop tension for corner removals below roof
- 180-degree hooks on vertical bars around bond beam bars at discontinuities
- No joint reinforcement

Detailing – Continuity

- Reinforced relief joints in lieu of control joints

TECH NOTE
CMU-TEC-009-23

CONCRETE MASONRY & HARDSCAPES ASSOCIATION

CRACK CONTROL STRATEGIES FOR CONCRETE MASONRY CONSTRUCTION

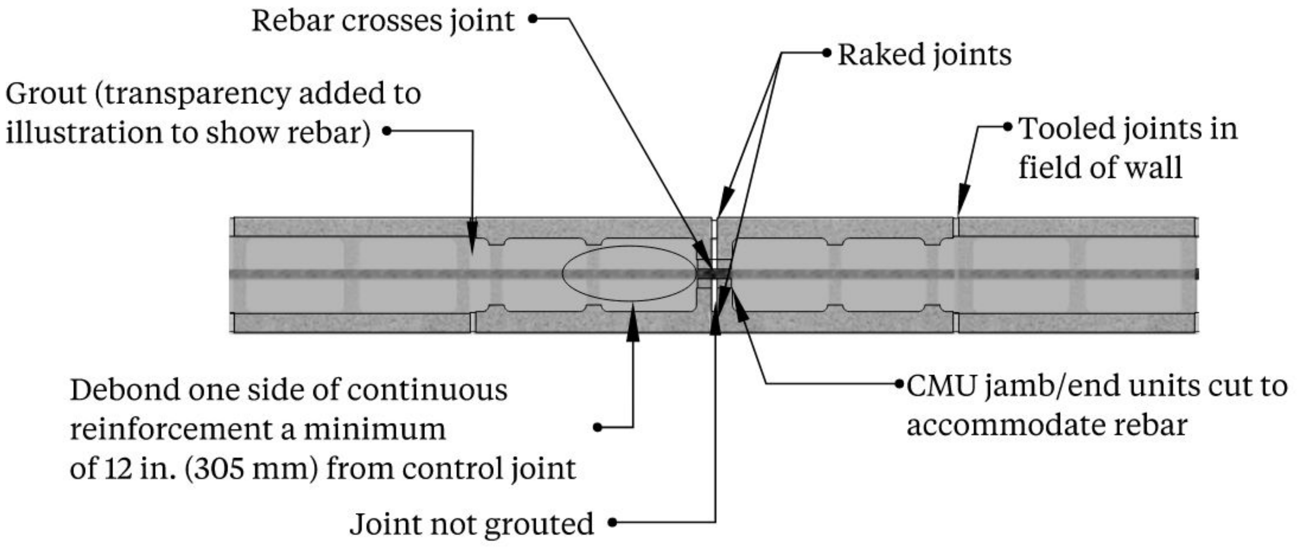
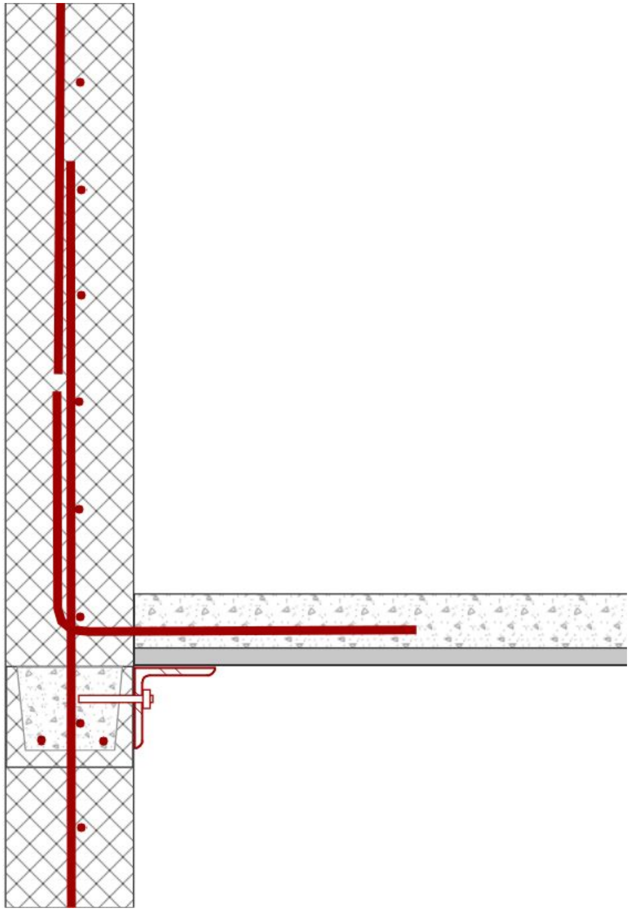


Figure 7j - Continuous horizontal reinforcement utilizing jamb units

Image Credits: https://www.masonryandhardscapes.org/resource/cmu-tec-009/

Detailing – Slab to Wall

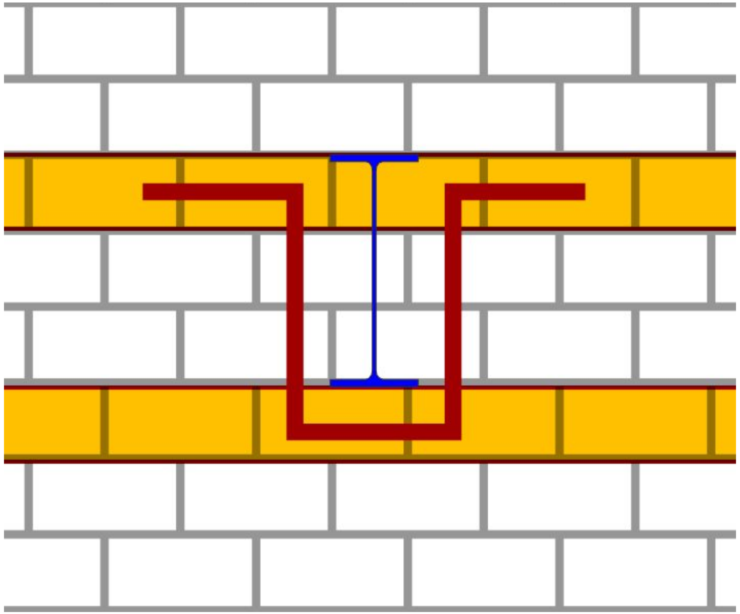
- Wall continuous, slab poured later
- Upturned slab dowels with contractor's option to provide threaded bar inserts instead
- Continuous angle supporting deck on inside face of masonry
- Wall vertical bar laps beyond upturned dowels



Detailing – Beam to Wall

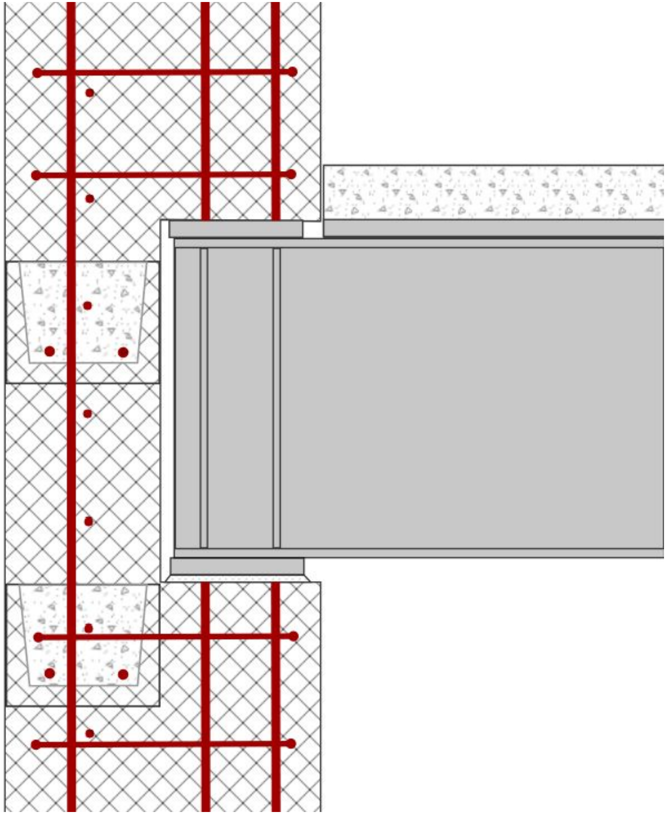
- Careful/strategic bond beam placement

- Saddle bars under beams bearing on wall



Detailing – Beam to Pilaster

- Wall and wall reinforcing continuous through pilaster
- Beam bondout
- Mechanical splices above/ below girders into pilasters for continuity of vertical reinforcement



Key Takeaways & Recommendations

- Not much cost added to upgrade to Progressive Collapse-Resistant reinforcement detailing - reinforced masonry is inherently redundant

- FEA best suited for AP analysis when gravity loads are applied at an eccentricity

- There are no analysis shortcuts - this takes a lot of time no matter which analysis approach is used

- Software available for staged structure removals is tuned for steel structures that experience large deformations

Key Takeaways & Recommendations

- More research effort, please!
  - Appropriate m-Factors for masonry functioning in a vertical in-plane/wall-beam flexural capacity
  - How should we define "h_{eff}" for wall removals?
  - Is there a better way to provide continuity through beams bearing on pilasters?
  - Develop some worked examples for insertion into UFC 4-023-03 appendices

THE MASONRY SOCIETY

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