Protection Engineering CONSULTANTS

A Principal and Senior Engineer at Protection Engineering Consultants, Mr. McKay has 20 years of experience as a structural engineer with focus in the security and protection engineering field. Mr. McKay regularly manages physical security and blast-resistant design (design-build, design-bid-build) efforts for large VA facilities, courthouses and other important federal buildings. Mr. McKay also has extensive experience in blast-resistant design of DoD and VA facilities. Mr. McKay has performed progressive collapse analysis and design for several buildings using both GSA and DoD standards, including assessments and retrofit designs for existing structures.

Progressive Collapse Mitigation

2022 ISEA Spring Conference

March 3, 2022

Introduction

- Aldo McKay, P.E
  - Managing Principal at PEC
  - 20 years of design experience. At PEC, regularly leads design efforts to mitigate progressive collapse
  - Lead researcher and contributor to the development of Load Increase and Dynamic Increase factors for the Alternate Path procedures currently in the UFC 4-023-03
  - Regularly teaches short courses and online webinars for the mitigation of progressive collapse.

Outline

1. History of Progressive Collapse Mitigation
2. Federal Design Standards
3. Overview of Design Methods
    - Tie Forces
    - Alternate Path
    - Threat Dependent Approach
- Summary

HISTORY AND DEFINITIONS

What is Progressive Collapse?

https://www.youtube.com/watch?v=EjOvI0TOx98

What is Progressive Collapse?

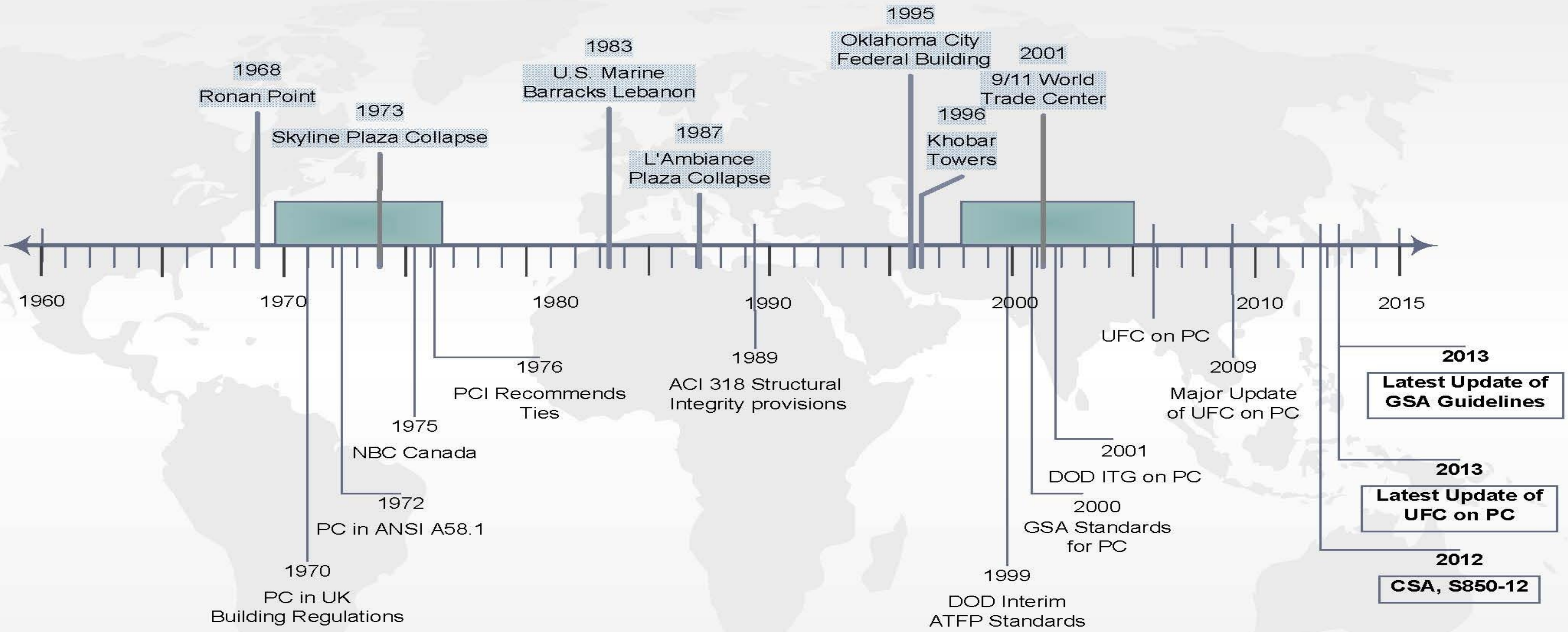
Definitions

- ASCE *Standard for Mitigation of Disproportionate Collapse Potential in Building and Other Structures* (in progress)
  - Disproportionate collapse: a collapse that is characterized by a pronounced disproportion between a relatively minor event and the ensuing collapse of a major part or the whole of a structure.

Definitions

- DoD Definition, 2016 (Adopted by GSA)
  - Definition in UFC 4-023-03 *Design of Buildings to Resist Progressive Collapse* is consistent with current U.S. standards – ASCE
  - Clarification is provided on intent
    - Initiating event is undefined
    - Hardening is not the intent
    - Goal is to prevent or minimize progressive collapse by ensuring redundancy and continuity in structural system
  - Local damage following initiating event
    - Not allowed for DoD
    - Partial damage allowed by GSA guidelines

Progressive Collapse Timeline



Ronan Point Apartments

- Watershed event for progressive collapse
- 22 story precast panel construction
- Gas explosion occurred in 18th story apartment
- Wall panel blew out, causing loss of support for 19-22nd floors
- Debris of upper floors caused floors below to successively collapse
- 5 people died, 17 hurt

Ronan Point Apartments

- Inquiry
  - Found no violation of any applicable building standard, nor defect in workmanship
  - Building standards gave detailed requirements for design of elements, but little guidance on stability of entire structural system
- Interesting facts
  - Precast panel construction fell out of favor and did not recover for many years.
  - Biscuit tin dent = 34 kN/m^2 (5 psi) for key elements

Murrah Federal Building, Oklahoma City

- April 19, 1995
- Approximately 4000 lb TNT
- Building was designed in early 1970s
- Nine story, reinforced concrete OMRF, one way slab system
- Transfer girder at third floor level supporting intermediate columns, providing 40-ft clear span for first two levels

Murrah Federal Building, Oklahoma City

- Whether this was progressive collapse is often debated
  - Was initial damage “local” or “global”?
- Changes in design to eliminate transfer girder, add continuity, and add ductility would have diminished extent of damage
- This event led to security criteria by the General Services Administration including design requirements for progressive collapse
- Event also influenced DoD to incorporate progressive collapse prevention into anti-terrorism criteria

Khobar Towers

- June 25, 1996
- Estimated weight of 20,000 lb TNT
- 19 fatalities, 500 wounded
- Many believe structure is example of preventing progressive collapse

DoD, VA and GSA

DESIGN STANDARDS

When is Progressive Collapse Design per DoD UFC 4-023-03 Required?

- DoD facilities worldwide must incorporate ATFP requirements per UFC *4-010-01(Minimum Antiterrorism Standards for Buildings*)
- ATFP considerations covered in 21 standards (UFC 4-010-01)
  - Site layout (setbacks, restricted zones, etc.)
  - Structural: **progressive collapse (Standard 6)**
  - Architectural: windows and structural supports, doors
  - Electrical and mechanical design
- Only for new inhabited buildings with 3 or more stories
  - Existing buildings do not require Progressive Collapse mitigation (2018 UFC 4-010-01)

DoD UFC 4-023-03

- *Design of Buildings to Resist Progressive Collapse*, Unified Facilities Criteria (UFC) 4-023-03, July 2009, Including Change 3, 1 November 2016
- Threat-independent
- Tie Forces, Alternate Path and Enhanced Local Resistance
  - Based on Risk Category

UFC 4-023-03
14 July 2009
Change 3, 1 November 2016

UNIFIED FACILITIES CRITERIA (UFC)

DESIGN OF BUILDINGS TO RESIST PROGRESSIVE COLLAPSE

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

Table 2-1. Risk Categories

Nature of Occupancy	\3\Risk Category/3/ [C]
• Buildings in Risk Category I in \1\ Table 2-2 of UFC 3-301-01. /1/ • Low Occupancy Buildings[A]	I
• Buildings in Risk Category II in \1\ Table 2-2 of UFC 3-301-01. /1/ • Inhabited buildings with less than 50 personnel, primary gathering buildings, billeting, and high occupancy family housing[A,B]	II
• Buildings in Risk Category III in \1\ Table 2-2 of UFC 3-301-01. /1/	III
• Buildings in Risk Category IV in \1\ Table 2-2 of UFC 3-301-01. /1/ • Buildings in Risk Category V in \1\ Table 2-2 of UFC 3-301-01. /1/	IV

[A] As defined by UFC 4-010-01 *DoD Minimum Antiterrorism Standards for Buildings*
[B] Risk Category II is the minimum occupancy category for these buildings, as their population or function may require designation as Risk Category III, IV, or V.
\2\ [C] Section 1604.5.1 Multiple occupancies of the International Building Code (IBC) is applicable for determination of the Risk Category including the provisions for structurally separated structures. /2/

Table 2-2. Risk Categories and Design Requirements

\3\ Risk Category /3/	Design Requirement
I	No specific requirements
II	Option 1: Tie Forces (TF) for the entire structure and Enhanced Local Resistance (ELR) for the corner and penultimate columns or walls at the first story. **OR** Option 2: Alternate Path (AP) for specified column and wall removal locations.
III	Alternate Path for specified column and wall removal locations and Enhanced Local Resistance (ELR) for all perimeter first story columns or walls.
IV[A]	Tie Forces and Alternate Path for specified column and wall removal locations and Enhanced Local Resistance for all perimeter first story columns or walls.

\3\ [A] For buildings in Risk Category IV in Table 2-2 of UFC 3-301-01, the minimum structural requirements for Tie Force application in Section 3-1.1 can be exempted. The minimum structural requirements shall remain for buildings in Risk Category V. /3/

U.S. Department of Veterans Affairs (VA)

- *VA PSRDM, 2020 (Revised September 2021)*
- Three stories or more
- New Construction
  - Based on building classification
  - Tie Forces, Alternate Path and Enhanced Local Resistance in accordance with UFC 4-023-03
- Existing Buildings
  - Threat-dependent Approach

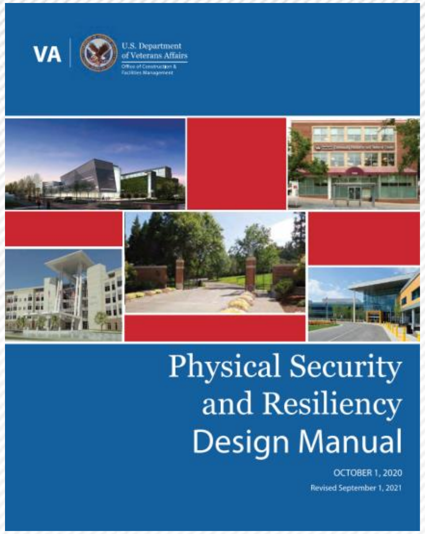


Table 7-3 Progressive Collapse Mitigation Methods

Criteria	Life-Safety Protected	Mission Critical
Three Stories or More	Tie Force Method	Tie Force Method, Enhanced Local Resistance Method, and Alternate Path Method

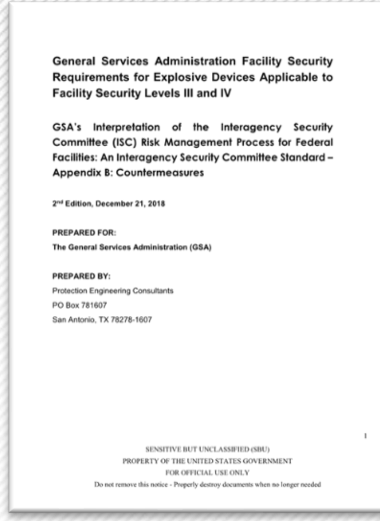
7.4.3 Alteration/Renovation of Existing Facilities — Progressive Collapse

In lieu of alternate path analysis, structural hardening/architectural treatment must be implemented per section 7.2.2 Vertical Structural Element Protection.

Federal Facilities Design Documents

The Risk Management Process for Federal Facilities, (2021 Edition)
- *Appendix E: How to Conduct a Facility Security Committee*
- *Appendix D: Use Physical Security Performance Measures*

GSA Interpretation, 2nd Edition (2018) and ASCE 59-11 Blast Protection of Buildings


General Services Administration Facility Security Requirements for Explosive Devices Applicable to Facility Security Levels III and IV

GSA's Interpretation of the Interagency Security Committee (ISC) Risk Management Process for Federal Facilities: An Interagency Security Committee Standard – Appendix B: Countermeasures

2nd Edition, December 21, 2018

PREPARED FOR:
The General Services Administration (GSA)

PREPARED BY:
Protection Engineering Consultants
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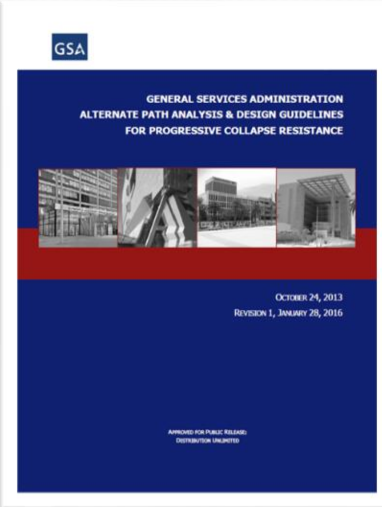
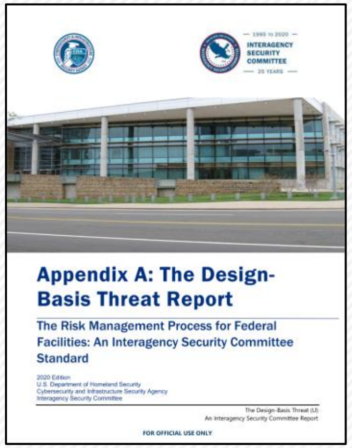
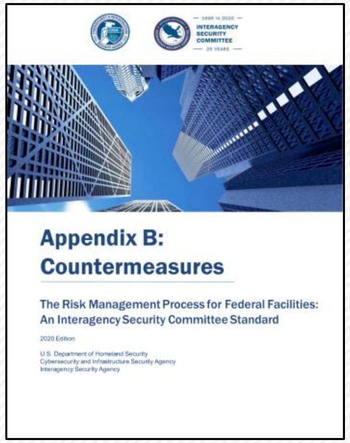
GSA AP Design Guidelines

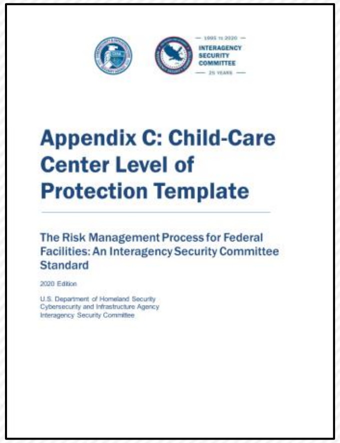




Appendix A: The DBT Report
2020 Edition



Appendix B: Countermeasures
(2020 Edition)



Appendix C: Child-Care Centers
Level of Protection Template (2020)

When to Apply GSA PC Guidelines?

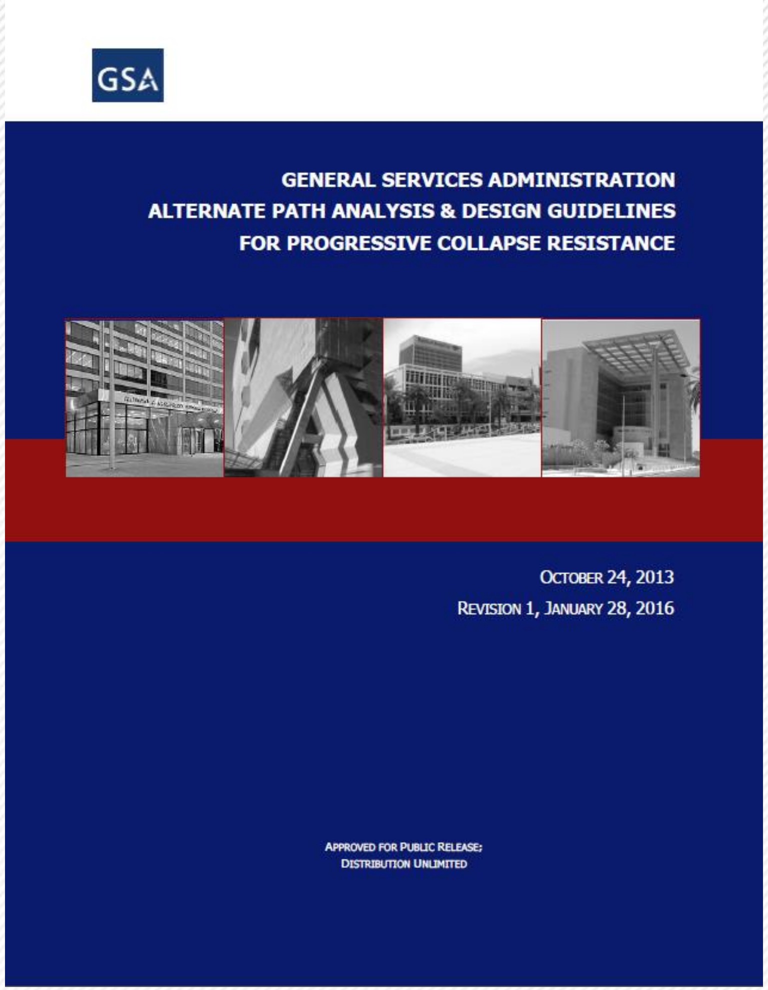
- The RMP for Federal Facilities: Appendix B: Countermeasures
  - FBI buildings, Courthouses
  - All new construction and additions
  - Existing buildings – only for major renovations

Facility Security Levels (FSLs)

Row ID	Security Criterion	Level I – Minimum	Level II – Low	Level III – Medium	Level IV – High	Level V – Very High	Details on Page
18	Blast Resistance - Progressive Collapse	No special measures required.	Use construction materials which have inherent ductility and which are better able to respond to load reversals (e.g., cast in place reinforced concrete and steel construction).	For buildings higher than three stories, use a combination of setback, site planning, façade hardening, and structural measures to prevent progressive collapse from the DBT or the loss of any single exterior column or load-bearing wall, whichever is lower.	For buildings higher than three stories, use a combination of setback, site planning, façade hardening, and structural measures to prevent progressive collapse from the DBT or the loss of any single exterior column or load-bearing wall, whichever is lower. Interior columns shall also be considered in buildings with an uncontrolled lobby.	For all buildings regardless of number of stories, use a combination of setback, site planning, façade hardening, and structural measures to prevent progressive collapse from the DBT or the loss of any single column, whichever is higher.	84

GSA Guidelines

- General Services Administration, *Alternate Path Analysis and Design Guidelines for Progressive Collapse Resistance* January 28, 2016
  - Philosophy, “Threat Dependent Approach”
    - May use hardening of specific load-carrying members
  - Alternate path based on methodology and performance requirements of UFC 4-023-03
  - Added “redundancy” requirement
  - Partial damage is allowed



GSA Guidelines - Applicability

- Clarification from GSA AP Guidelines
- FSL III and IV with **four (4)** or more stories
  - Unoccupied floors don't count (ex: mechanical penthouses)
  - AP and redundancy requirements must be met
  - Exterior removals are at first floor above grade
- FSL V buildings **regardless** of number of stories
  - FSL V requires removal analysis at all floors
  - Redundancy procedures do not apply, just AP at prescribed locations

Tie Forces, Alternate Path (Linear static, nonlinear dynamic), and Threat Dependent

PROGRESSIVE COLLAPSE DESIGN METHODS

Indirect Design

- Indirect design refers to design methodologies that ***implicitly*** consider resistance to progressive collapse
  - Tie Force Method (TF)
  - Enhanced Local Resistance (ELR)

- Achieve collapse resistance by specifying ***general requirements*** for strength, continuity and ductility in key areas without considering a specific initiating event or threat scenario

Direct Design

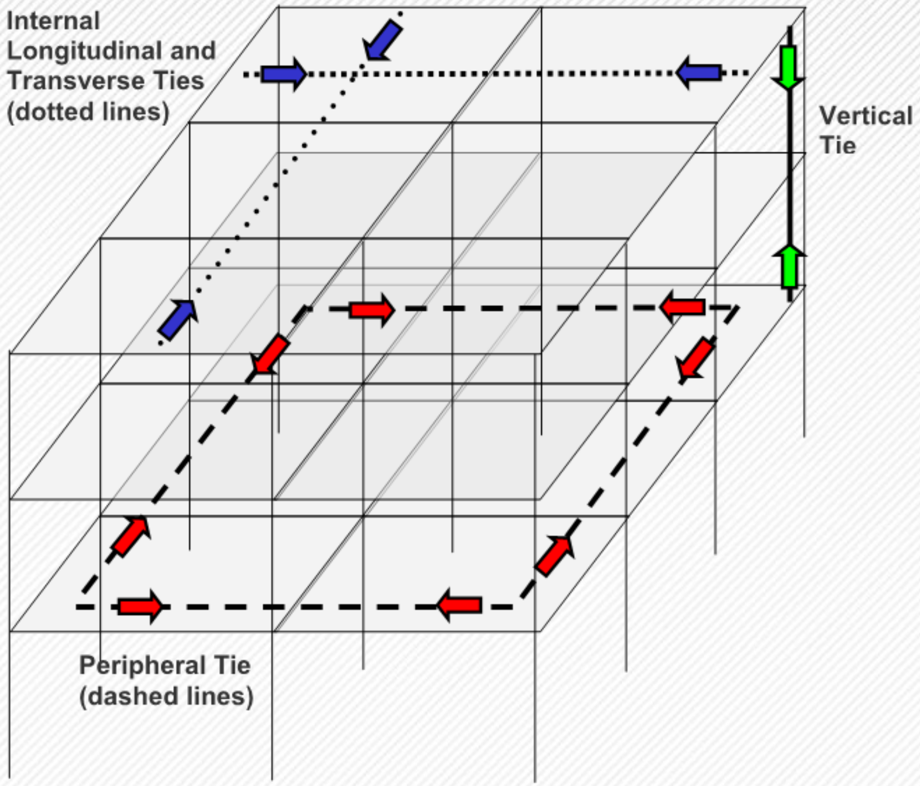
- Direct design refers to design methodologies that ***explicitly*** consider resistance to progressive collapse
  - Specific Local Resistance (SLR) or Threat-Dependent Approach
  - Alternate Path (AP)

- Consider a ***specific*** threat or damage scenario and design for that case
  - e.g. explosive threat, column removal scenario, etc.

TIE FORCES APPROACH

Tie Forces (*Not allowed in GSA Guidelines*)

- **Gravity loads** define required **tie strengths**
- **Building geometry** defines **tie distribution** and **location**
- Continuity of ties is necessary to ensure proper response in progressive collapse scenario

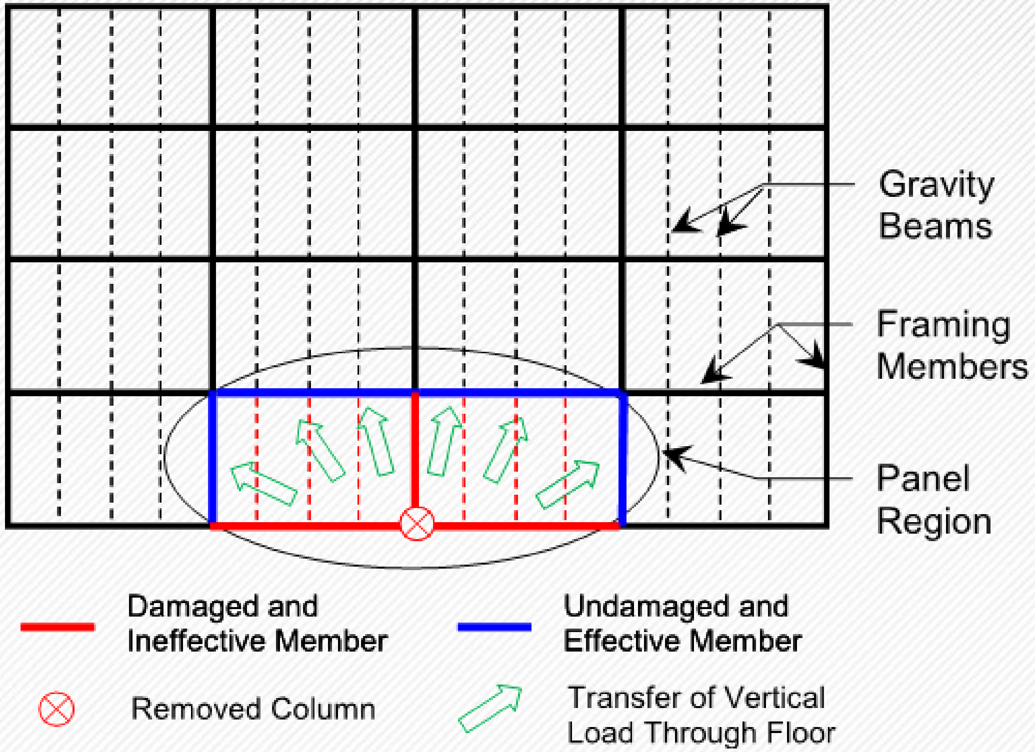


UFC 4-010-01 (2013)

Figure 3-1. Tie Forces in a Frame Structure

Purpose of Ties

- Ties provide an alternative load-transfer mechanism for gravity loads if critical load-bearing elements are damaged (e.g. column removal)
  - Distributed for robustness and redundancy
  - Assumed to act as catenary elements (post-flexure levels of deformation)
  - Tie forces can be provided by existing structural elements that have been designed for standard loads
    - Primary members have additional requirements (next slide)
  - Floor and roof systems are the preferred location for ties
    - CIP concrete, composite concrete on metal deck, precast floor with CIP topping slab, etc.



UFC 4-010-01 (2013)

Figure C-1. Damaged and Undamaged Structural Elements (Plan View)

General Steps for Tie Force Method

- Calculate floor load
  - May use sub-areas

$w_F = 1.2D + 0.5L$ Equation (3-2)

Where w_F = Floor Load (lb/ft^2 or kN/m^2)

D = Dead Load (lb/ft^2 or kN/m^2)

L = Live Load (lb/ft^2 or kN/m^2)

- Calculate tie strength requirements
  - Internal ties (*Fi*)

$F_i = 3\, w_F\, L_1$ Equation (3-3)

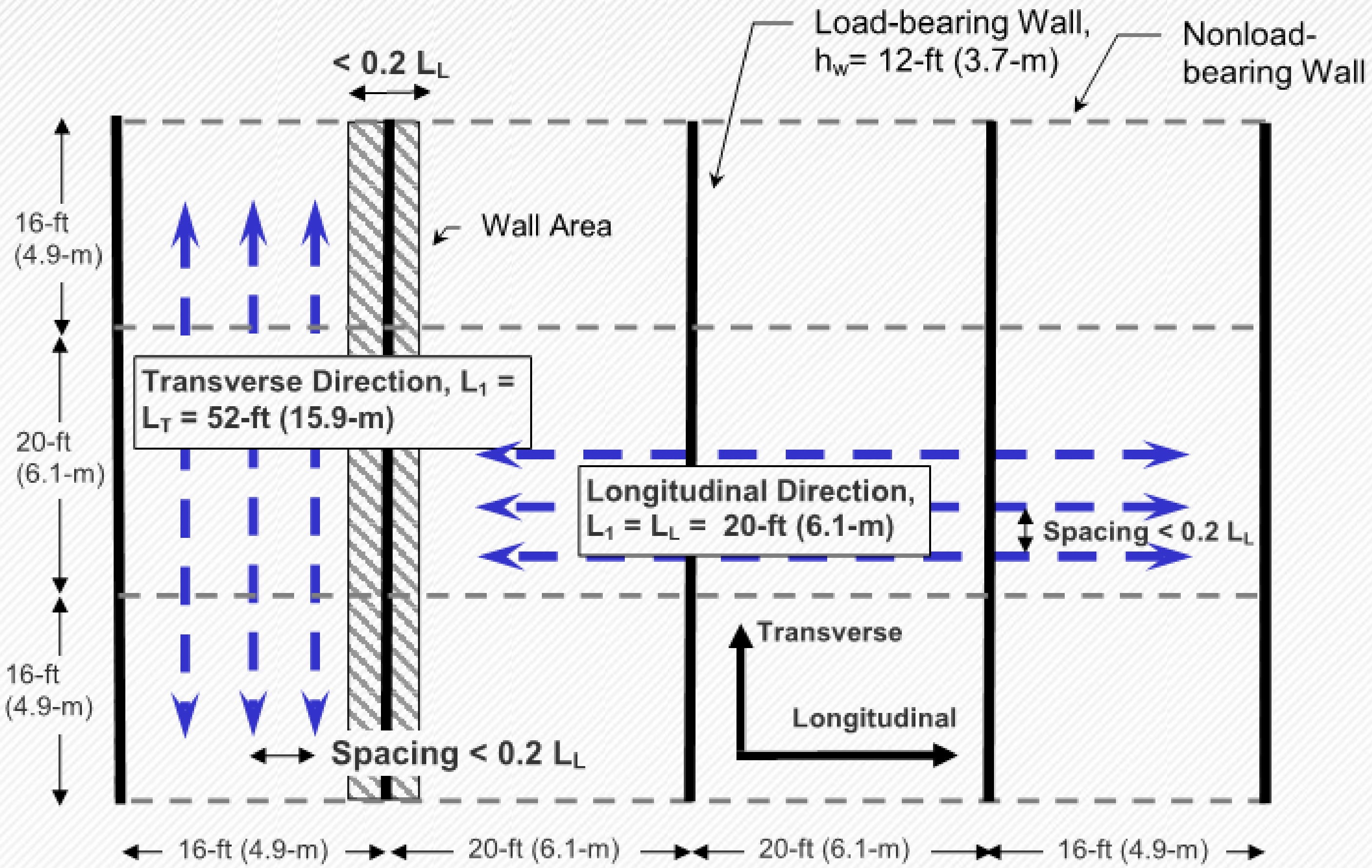
  - Peripheral ties (*Fp*)

$F_p = 6\, w_F\, L_1\, L_p + 3\, W_C$ Equation (3-6)

  - Vertical ties
    - design strength in tension equal to the largest vertical load received by the column or wall from any one story, using the **tributary area** and the floor load w_F

Internal Tie Strength Example

Figure 3-5. Determination of L_1 and Column Area for One-way Load-bearing Wall Construction with h_w = 12-ft (3.7-m)



- L_L = 20-ft
- L_T = min ($5h_{w,}$ W)
  = 52-ft
- w_F = 100-psf
- **F_L = 3(100)(20)**
  = 6-kip/ft
- **F_T = 3(100)(52)**
  = 15.6-kip/ft

General Steps for Tie Force Method, Cont'd

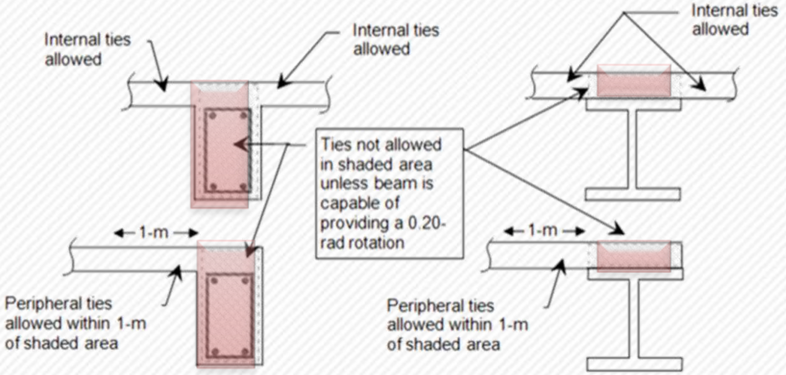
- Provide require strengths
  - LRFD Approach
  - Separately from other forces acting on the tie element
- Meet detailing, distribution and placement requirements
  - Continuity, splices, etc.

$$\Phi R_n \geq R_u \qquad \text{Equation (3-1)}$$

where

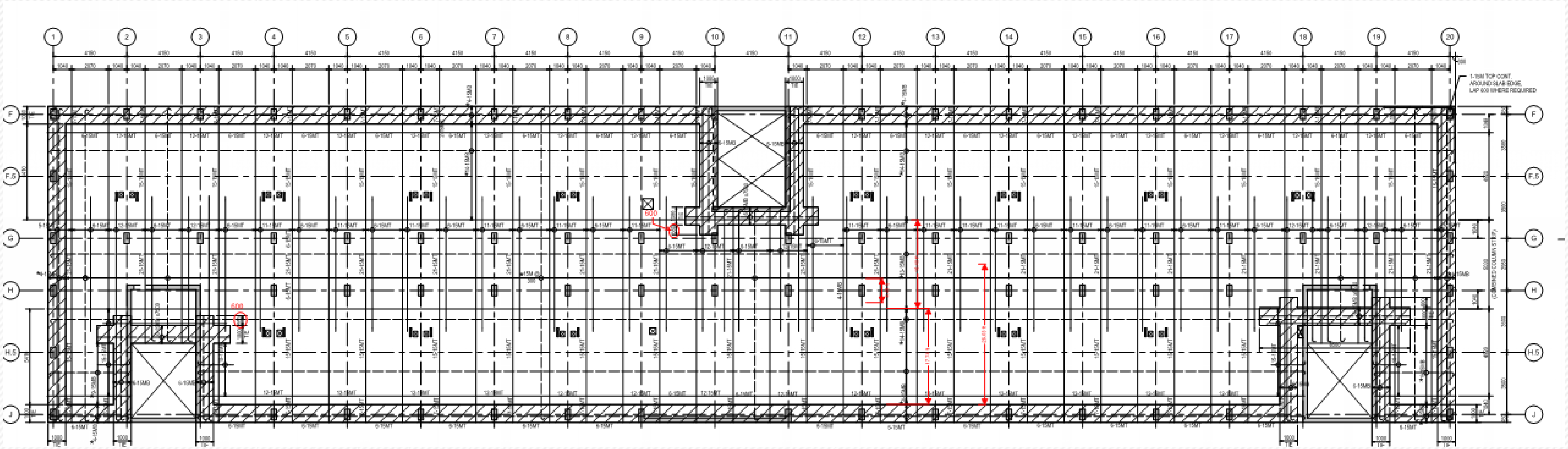
ΦR_n = Design tie strength
Φ = Strength reduction factor
R_n = Nominal tie strength calculated with the appropriate material specific code, **including the over-strength factors from Chapters 5 to 8 of ASCE 41.**
R_u = $\Sigma \gamma_i Q_i$ = Required tie strength
γ_i = Load factor
Q_i = Load effect

Figure 3-4. Location Restrictions for Internal and Peripheral Ties That are Parallel to the Long Axis of a Beam, Girder or Spandrel

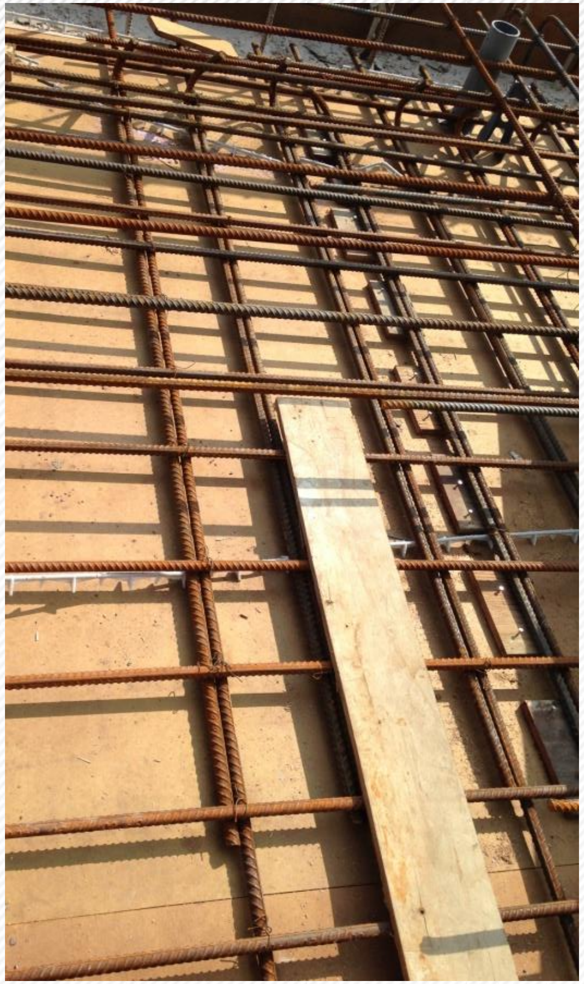


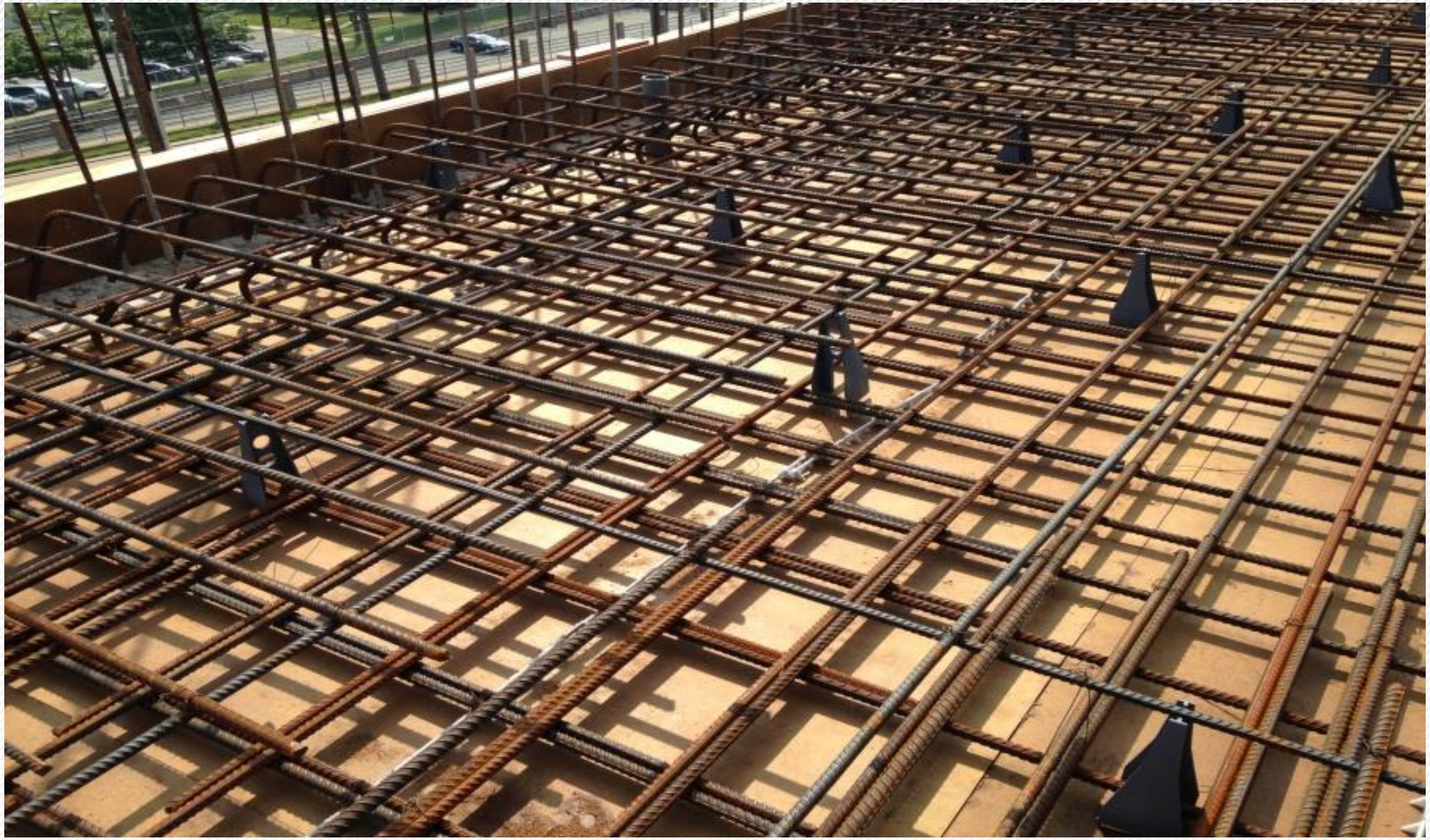
Tie Forces

- Real structures are often not as clean as code diagrams
- Care must be taken in defining tie types and layout

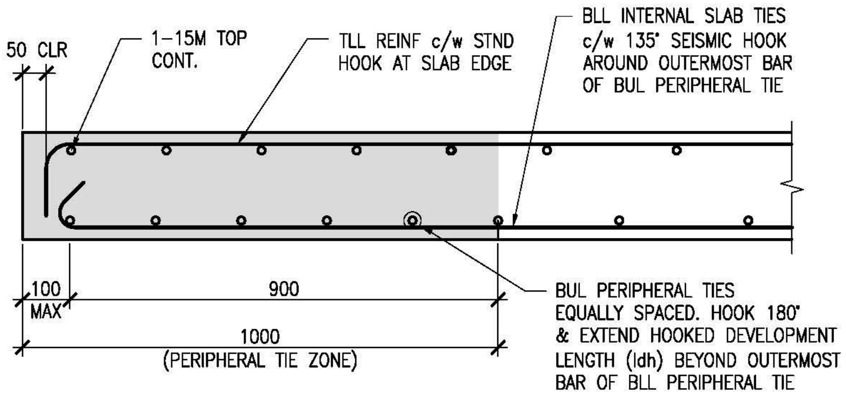


Internal Ties

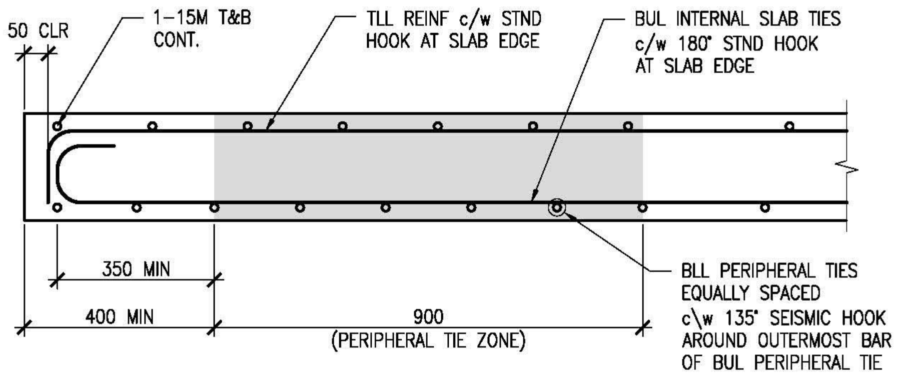




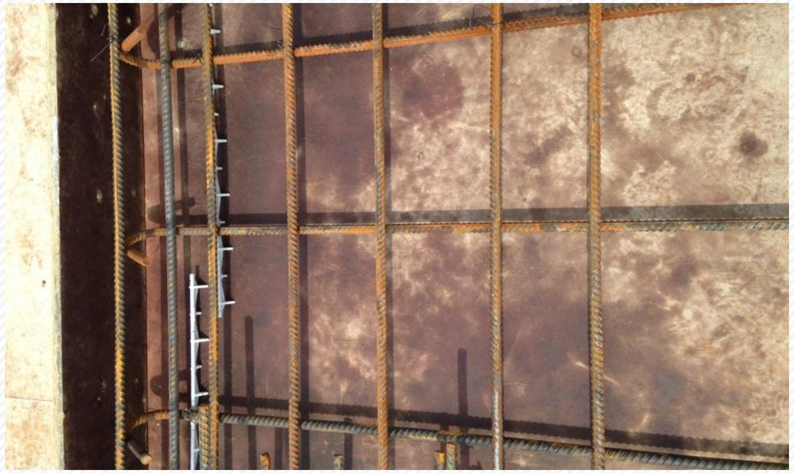
Peripheral Ties



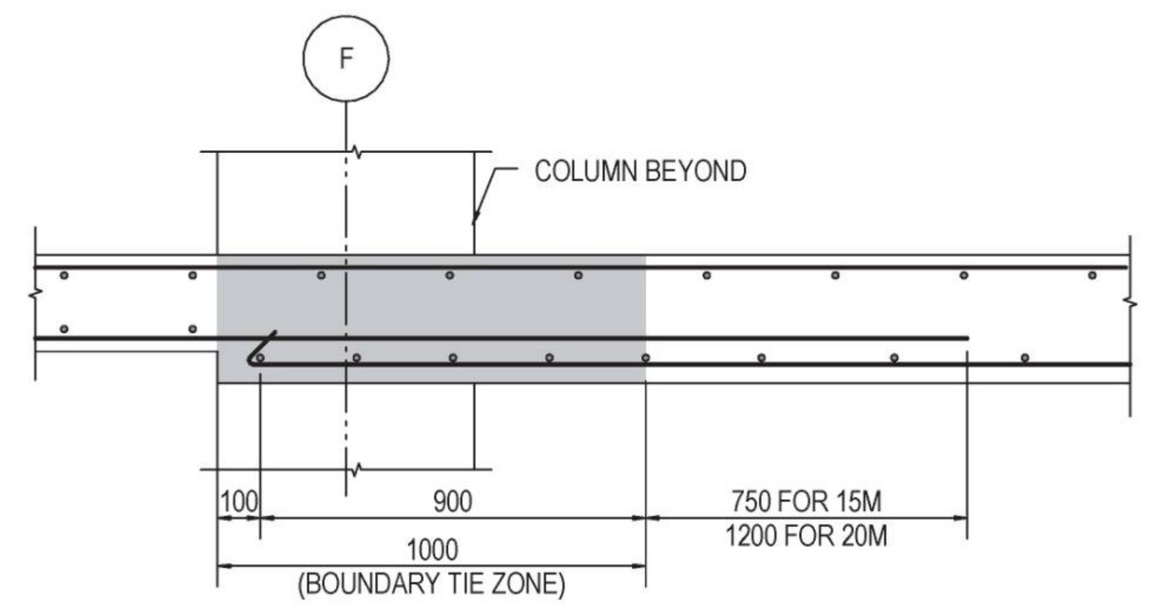
BUL PERIPHERAL TIES AT SLAB FREE EDGE



BLL PERIPHERAL TIES AT SLAB FREE EDGE



Sub-area Peripheral Tie

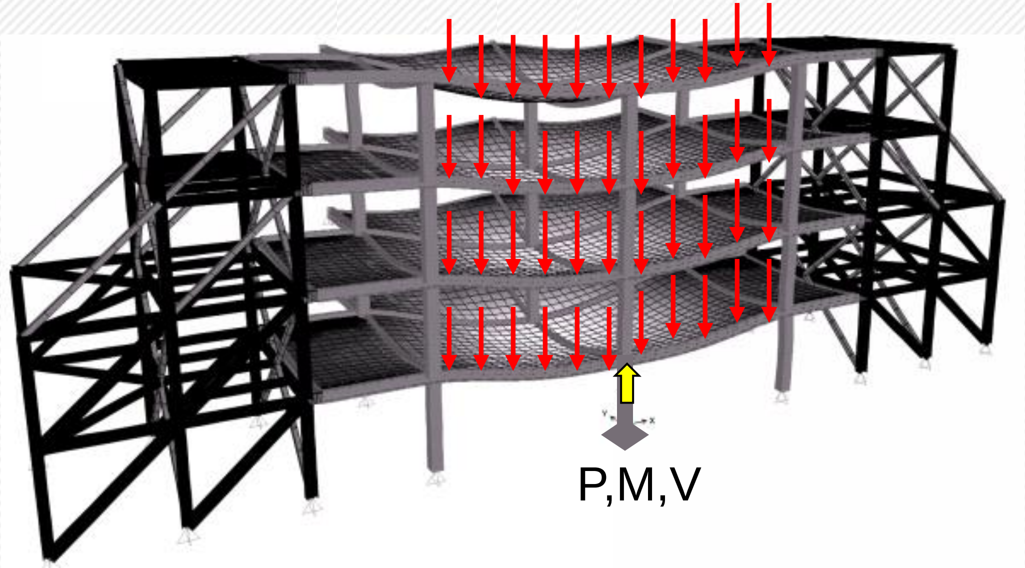


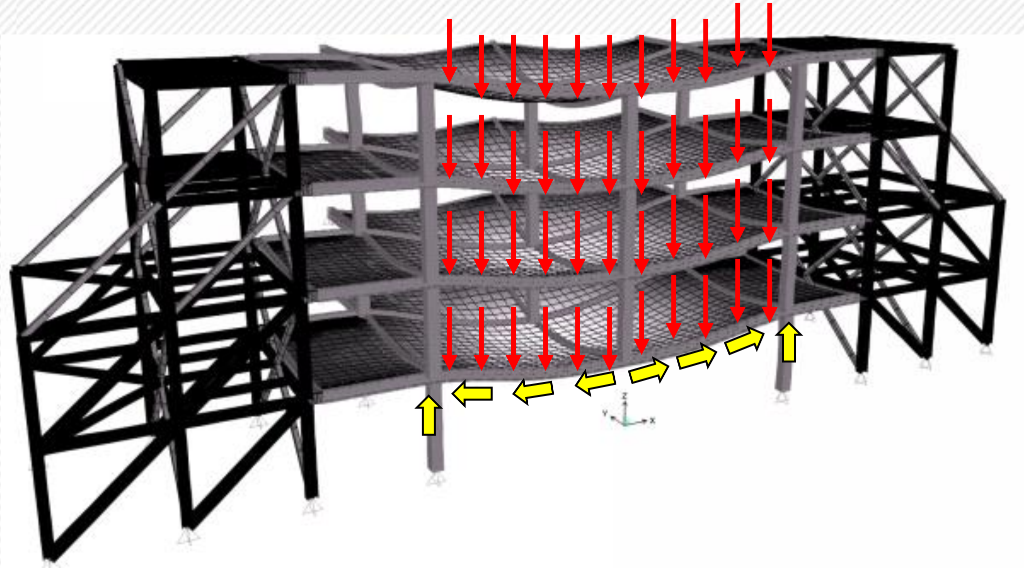
Boundary Peripheral Tie at Change in Slab Thickness

DOD UFC 4-023-03 and GSA Alternate Path Guidelines

ALTERNATE PATH

What is Alternate Path Analysis?





- **Normal Condition**

- **Direct Method of Analysis**
- **Goal is to show that the structure can bridge over a missing load-bearing element**

Alternate Path (Covered in § 3-2)

General Information and Requirements - § 3-2.1

- Use LRFD philosophy by employing the ASCE 7 load factor combination for extraordinary events and resistance factors to define design strengths.
- **Three analysis procedures are employed: Linear Static (LSP), Nonlinear Static (NSP) and Nonlinear Dynamic (NDP).**
- Material-specific modeling (Hinges, etc..) criteria from Chapters 5 to 8 of ASCE 41 are explicitly adopted in Chapters 4 to 8 of this document.
    - Steel or cast iron, ASCE 41-06 Chapter 5 (ASCE 41-13 Chapter 9)
    - Reinforced concrete, ASCE 41-06 Chapter 6 (ASCE 41-13 Chapter 10)
    - Reinforced or un-reinforced masonry, ASCE 41-06 Chapter 7 (ASCE 41-13 Chapter 11)
    - Timber and CFS, ASCE 41-06 Chapter 8 (ASCE 41-13 Chapter 12)
- Note that some of the deformation and strength criteria in ASCE 41-06 Ch. 5 to 8 have been superseded by requirements that are specified in the material specific Chapters 4 to 8 in GSA guidelines – similar for ASCE 41-13 Ch. 9 to 12 by UFC 4-023-03 (2016)

LRFD Approach

- *Φ*, strength reduction factors are used, unlike ASCE 41
  - Refer to material specific codes for phi-factors
- Include over-strength factors provided in ASCE 41 (2006 / 2013)
  - Tables 5-3 / Table 9-3 (structural steel)
  - Table 6-4 / Table 10-1 (reinforced concrete)
  - Table 7-2 / Table 11-1 (masonry)
- Live load reductions are permitted and guidance provided
  - Calculate live load reduction based on structural configuration prior to load-bearing element removal

Expected and Lower Bound Strength

- **Covered in § 3-2.6**
  - For deformation-controlled actions, use the **expected strength**
    - If not available, use the design strength, multiplied by the over-strength factor Ω (provided in ASCE 41)
  - For force-controlled actions, use a **lower bound strength**
    - If not available, use the design strength
    - **OVER-STRENGTH FACTOR IS NOT USED**

Material Properties

- **Covered in § 3-2.7**

ASCE 41-06 – OSF for Structural Steel (Partial Table)

Table 5-3 Factors to Translate Lower-Bound Steel Properties to Expected-Strength Steel Properties

Property	Year	Specification	Factor
Tensile Strength	Prior to 1961		1.10
Yield Strength	Prior to 1961		1.10
Tensile Strength	1961-1990	ASTM A36/A36M-00	1.10
	1961-present	ASTM A572/A572M-89, Group 1	1.10
		ASTM A572/A572M-89, Group 2	1.10
		ASTM A572/A572M-89, Group 3	1.05
		ASTM A572/A572M-89, Group 4	1.05
		ASTM A572/A572M-89, Group 5	1.05
	1990-present	ASTM A36/A36M-00 & Dual Grade, Group 1	1.05
		ASTM A36/A36M-00 & Dual Grade, Group 2	1.05
		ASTM A36/A36M-00 & Dual Grade, Group 3	1.05
		ASTM A36/A36M-00 & Dual Grade, Group 4	1.05

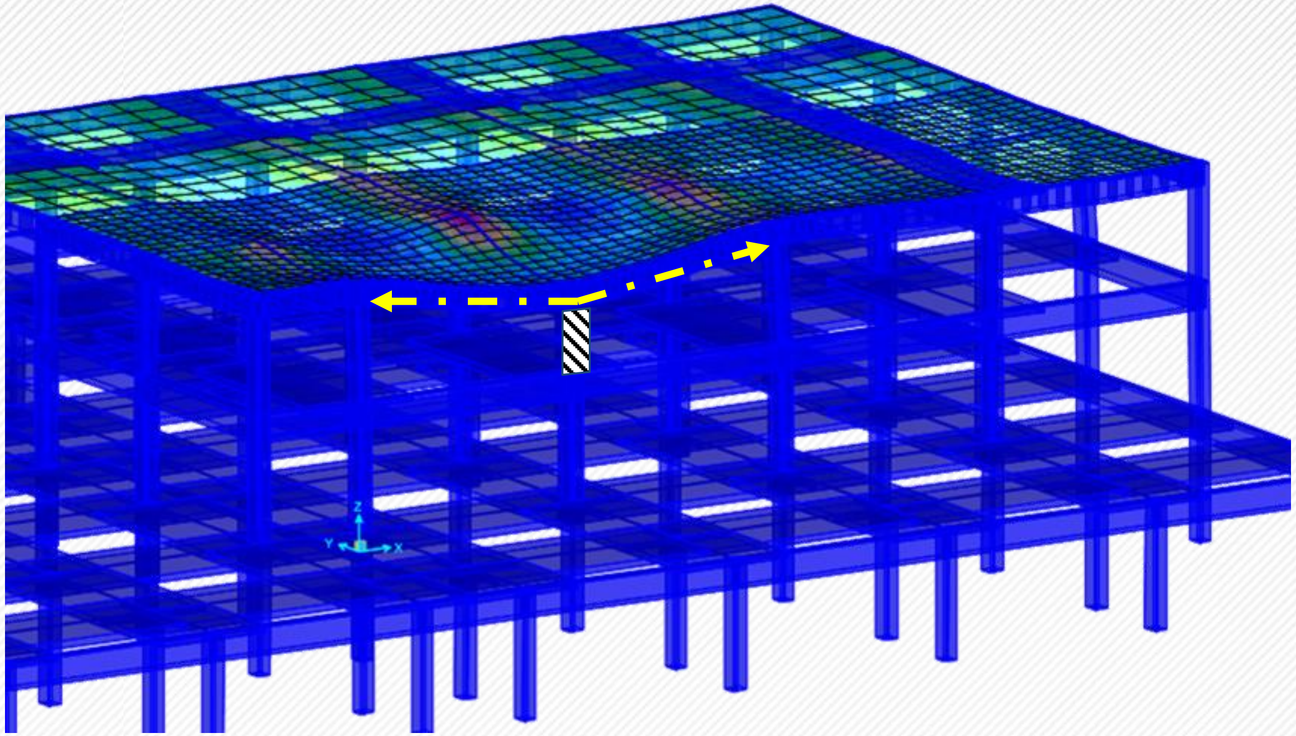
ASCE 41-06 – OSF for RC

Table 6-4 Factors to Translate Lower Bound Material Properties to Expected Strength Material Properties

Material Property	Factor
Concrete Compressive Strength	1.50
Reinforcing Steel Tensile & Yield Strength	1.25
Connector Steel Yield Strength	1.50

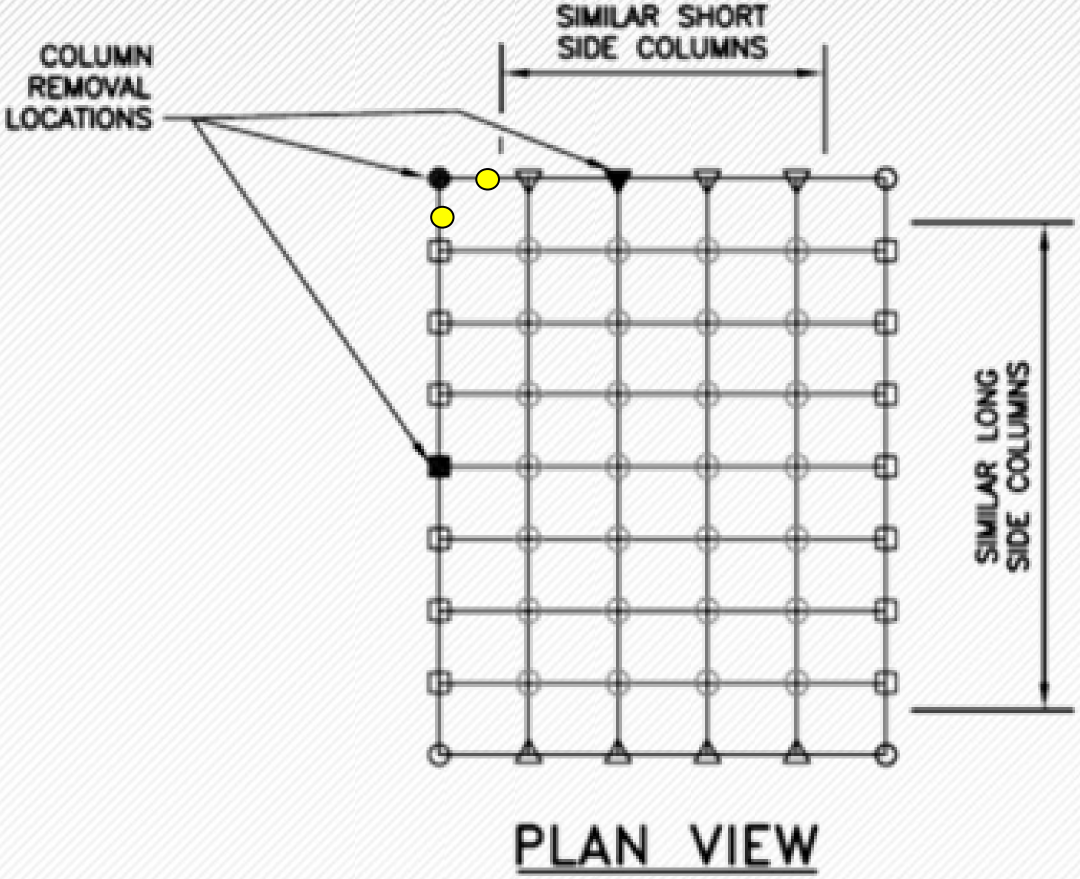
Removal of Load-Bearing Elements

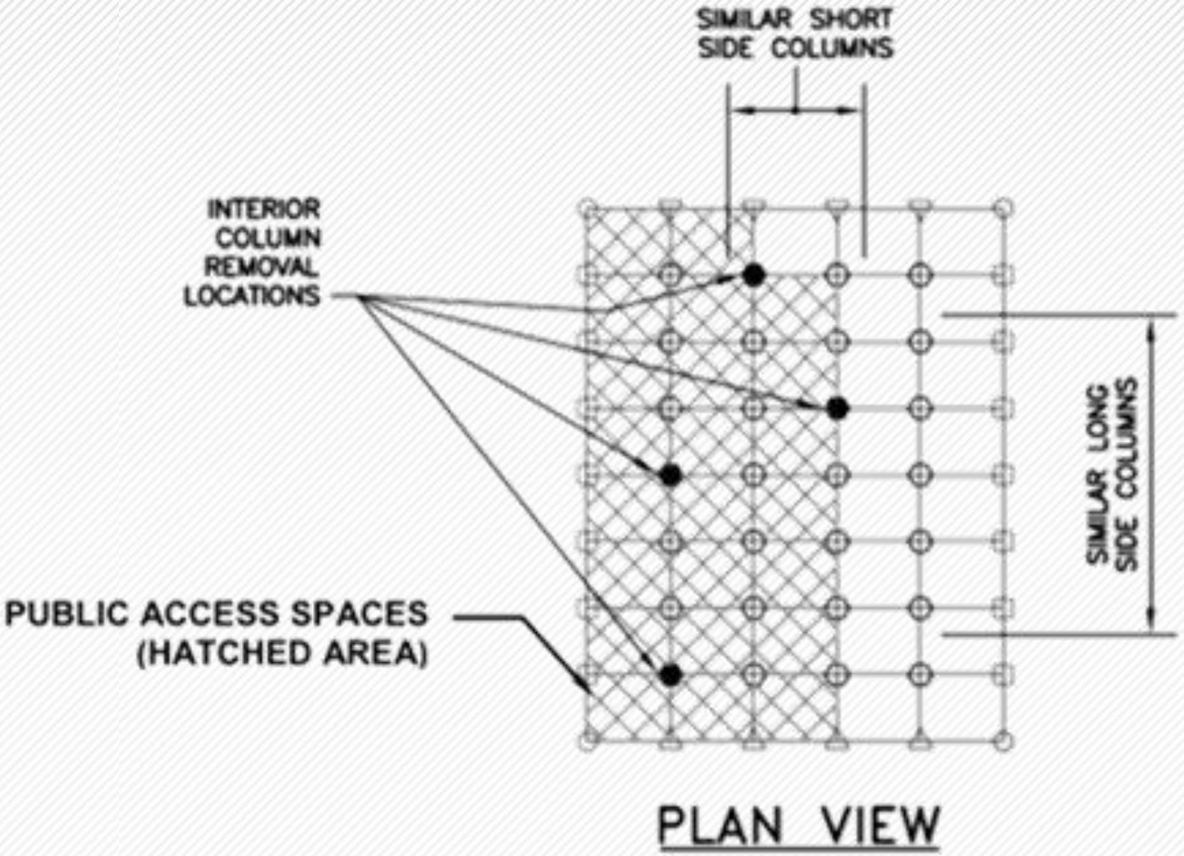
- **Covered in § 3-2.9**
- For both external and internal removal scenarios, it is assumed that **beam-to-beam continuity is maintained** across the removed column



Must maintain beam-to-beam continuity across a removed element!

Location of Removed Elements





Any other load-bearing element within a distance of 30% of the largest dimension of the associated bay from the removal location must be removed simultaneously.

Structure Acceptance Criteria, New Buildings (DoD, VA and GSA)

- **Covered in § 3-2.10.1**

For all three analysis types (LS, NS, and ND), the building is structurally adequate if none of the primary and secondary elements, components, or connections exceeds the acceptance criteria, in Paragraphs 3-2.11.7, 3-2.12.7, and 3-2.13.6, as appropriate. If the analysis predicts that **any** element, component, or connection does not meet these acceptance criteria, the building does not satisfy the progressive collapse requirements and must be re-designed.

No partial damage allowed. All components, connections, etc must meet acceptance criteria!!

Structure Acceptance Criteria – Existing Buildings (GSA Only)

- Allowable extent of Collapse

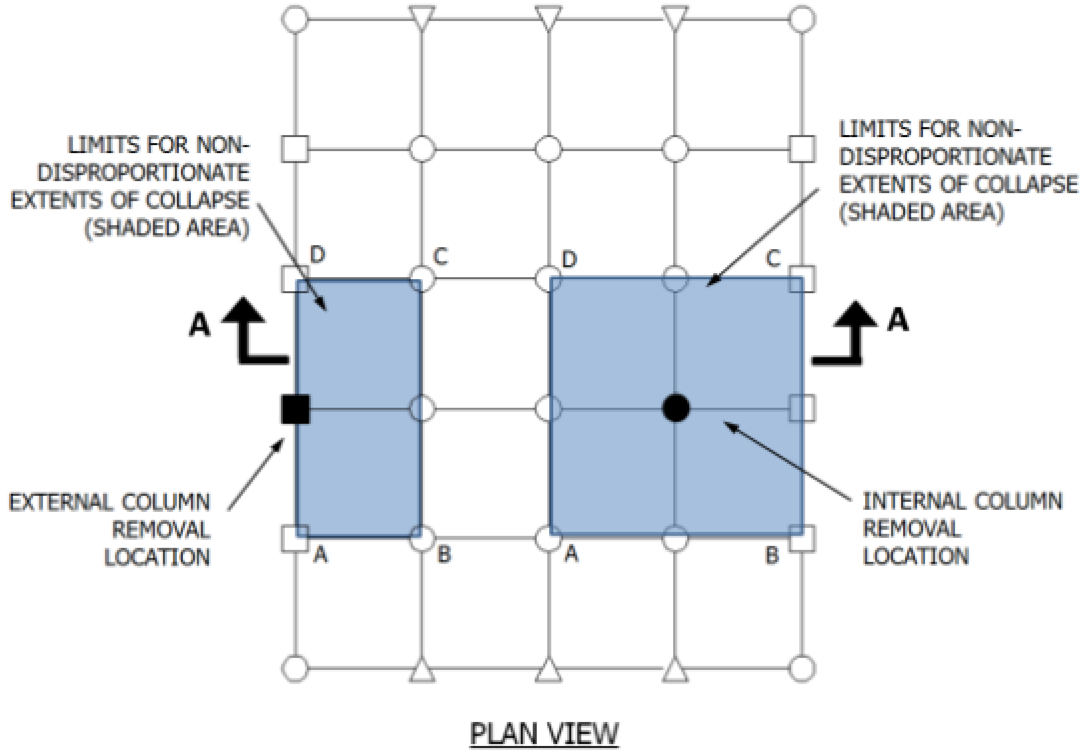


Figure 3.13. Allowable Extents of Collapse for Interior and Exterior Column Removal in Plan

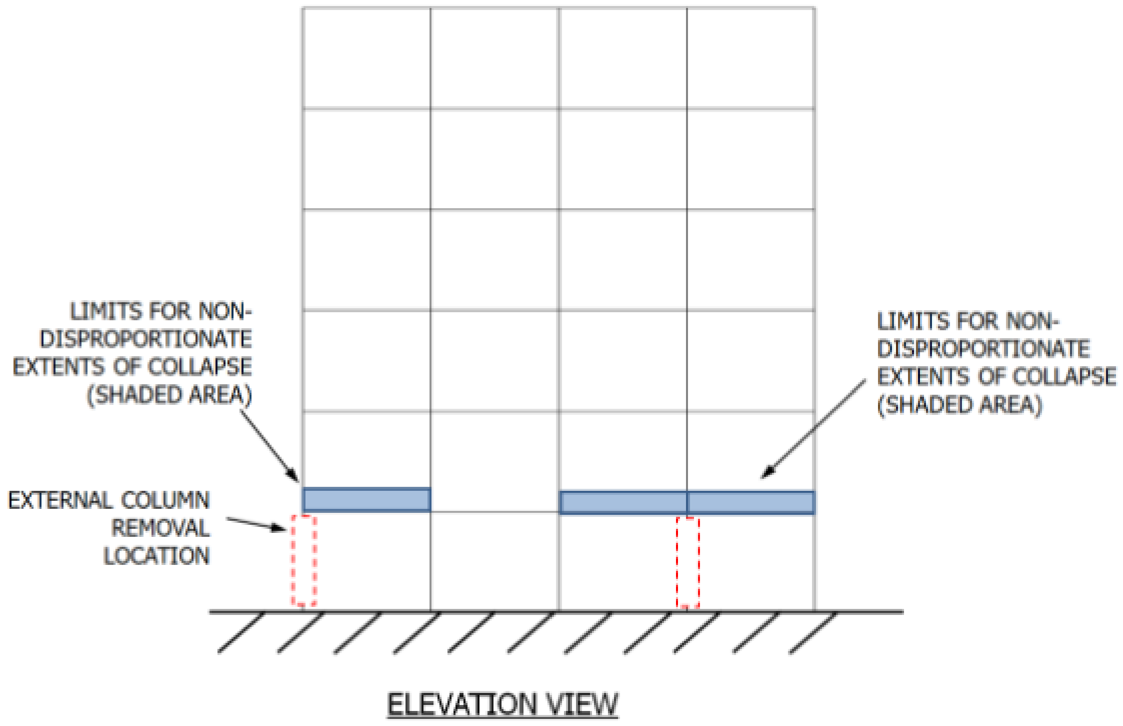


Figure 3.14. Allowable Extents of Collapse for Interior and Exterior Column Removal in Elevation

Analysis Procedures

- Three analysis procedures are used
  - Linear Static
    - Uses load increase factor (LIF) to approximately account for inertial or nonlinear effects
    - In theory the simplest to apply but actually requires a fair amount of work
    - Because it's "simple", it has to be conservative
  - Nonlinear Static
    - Directly accounts for nonlinearity but a dynamic increase factor (DIF) is needed to account for inertia effects
    - Not as conservative
  - Nonlinear Dynamic Most realistic
    - Least conservative

Linear Static Alternate Path Analysis Main Steps

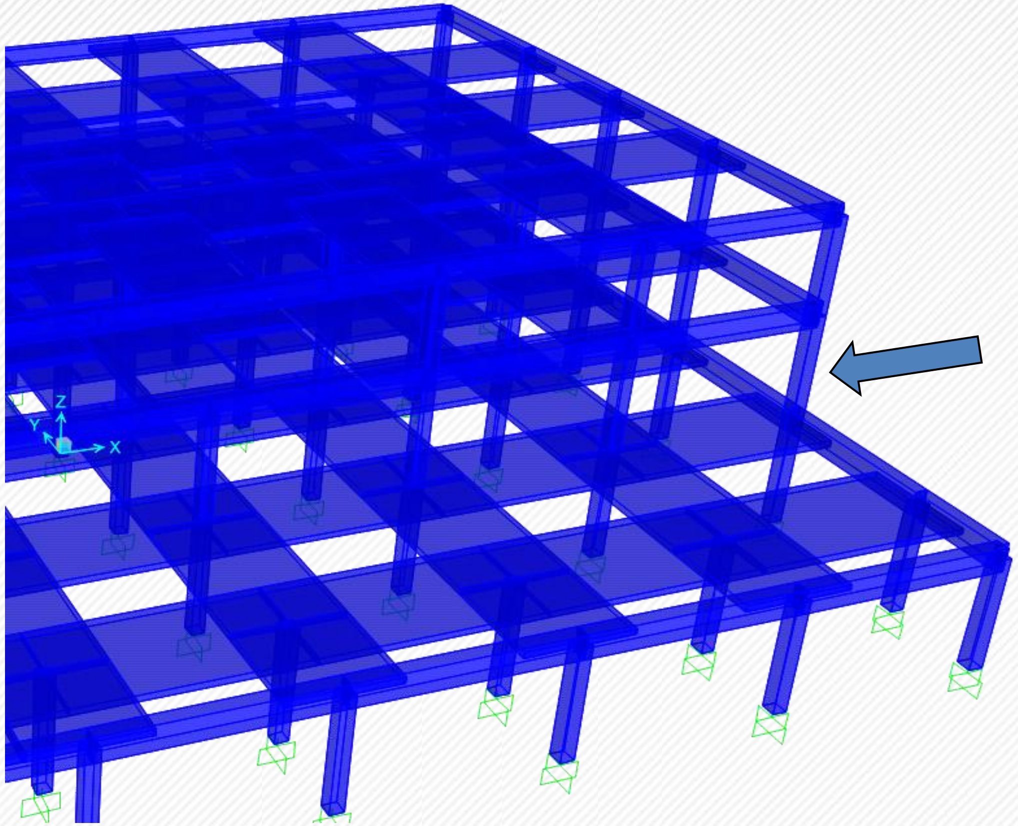
1. Check for irregularities
2. Start with model sized for base code strength and project serviceability requirements without consideration of progressive collapse
3. LS AP Analysis Steps:
   a) Remove load-bearing element from model
   b) Determine applicable m-factors and calculate , Ω_{LD} and Ω_{LF}
   c) Using PC load case, add extra loads around loss location
   d) Analyze model with column removed and determine deformation controlled and force controlled elements
   e) Evaluate adequacy (Acceptance criteria)
   f) Identify and check adjacent secondary beams

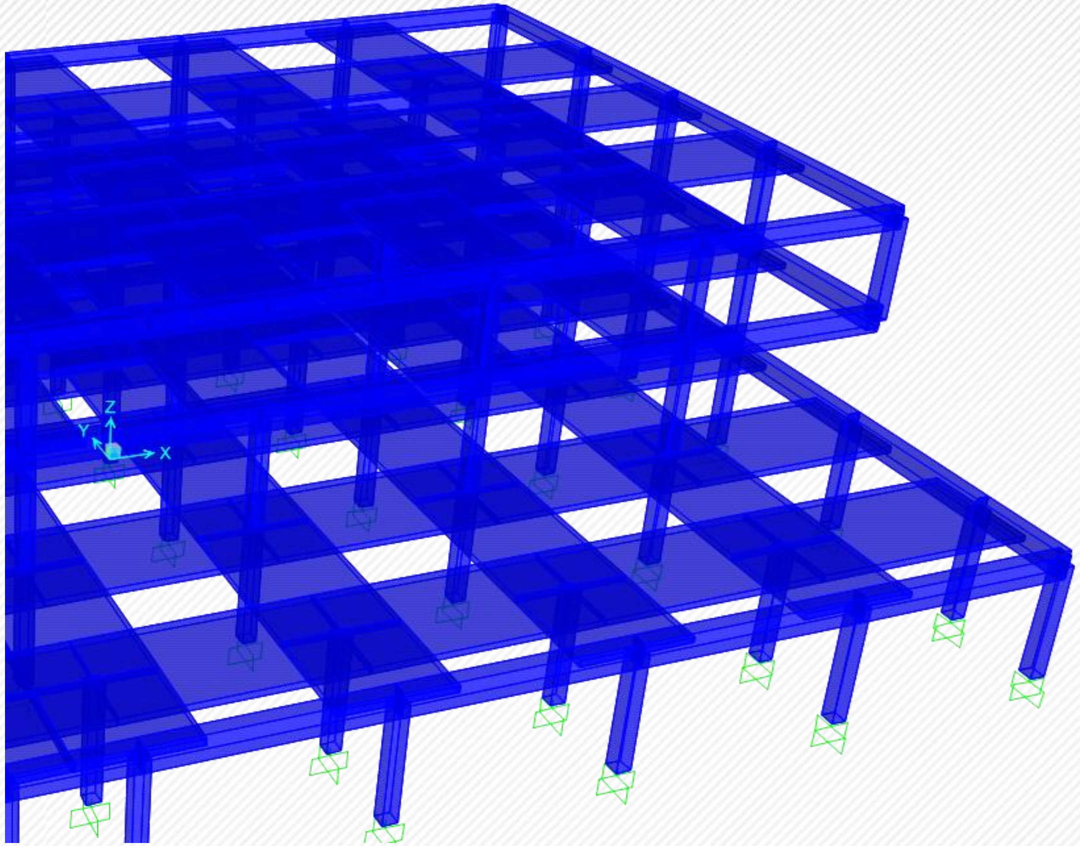
Load Increase Factor - Example

- Calculate m factors for all primary elements connected to loss location and above (within region of load increase)
- m Factors taken where flexural nonlinearity is expected to occur (i.e. where hinges would be placed)
- *m* is the *m*-factor defined in Chapters 4 to 8 of the UFC
- Columns not included…
- **Take smallest *m***

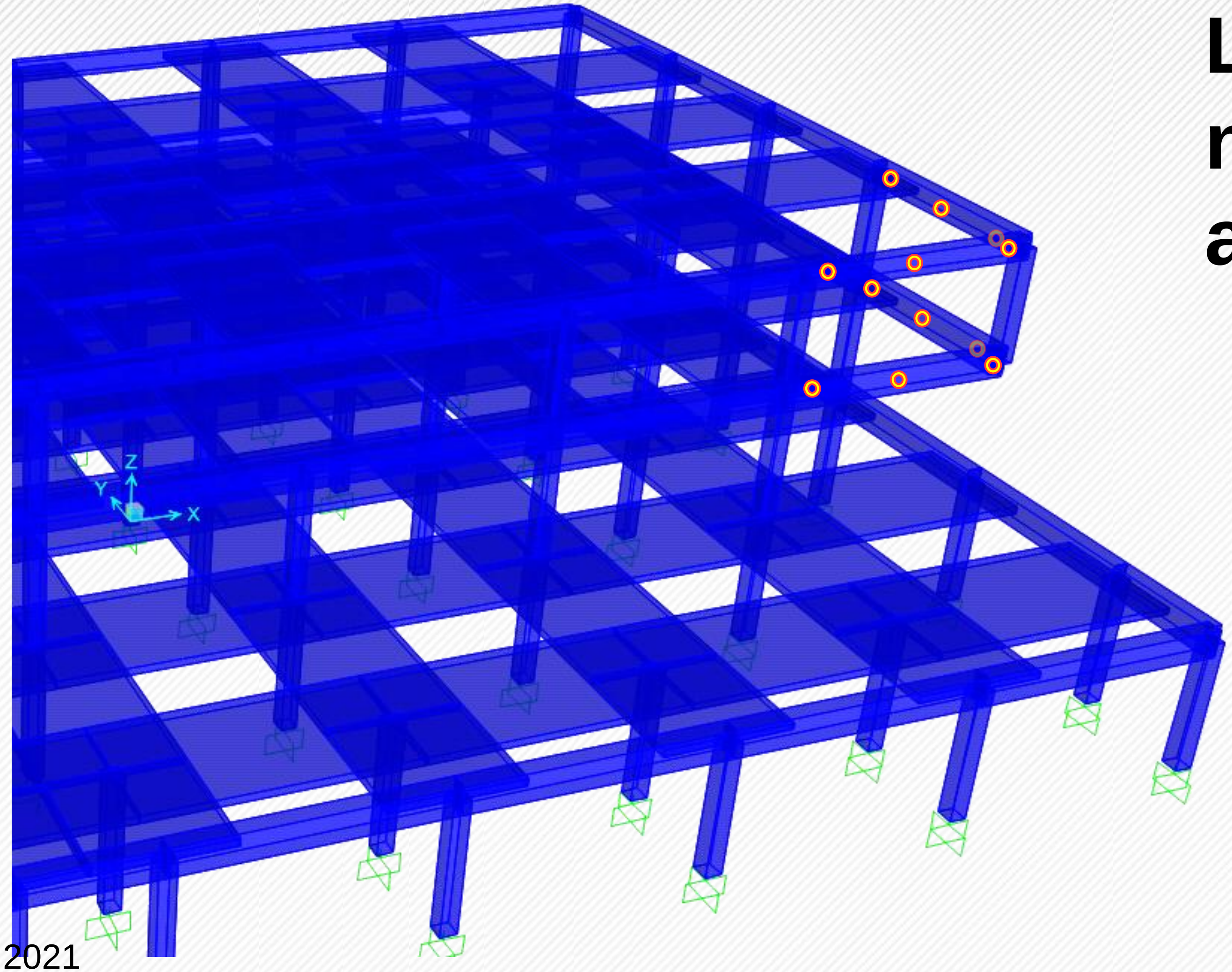
Load Increase Factor – Example

Reinforced Concrete Building



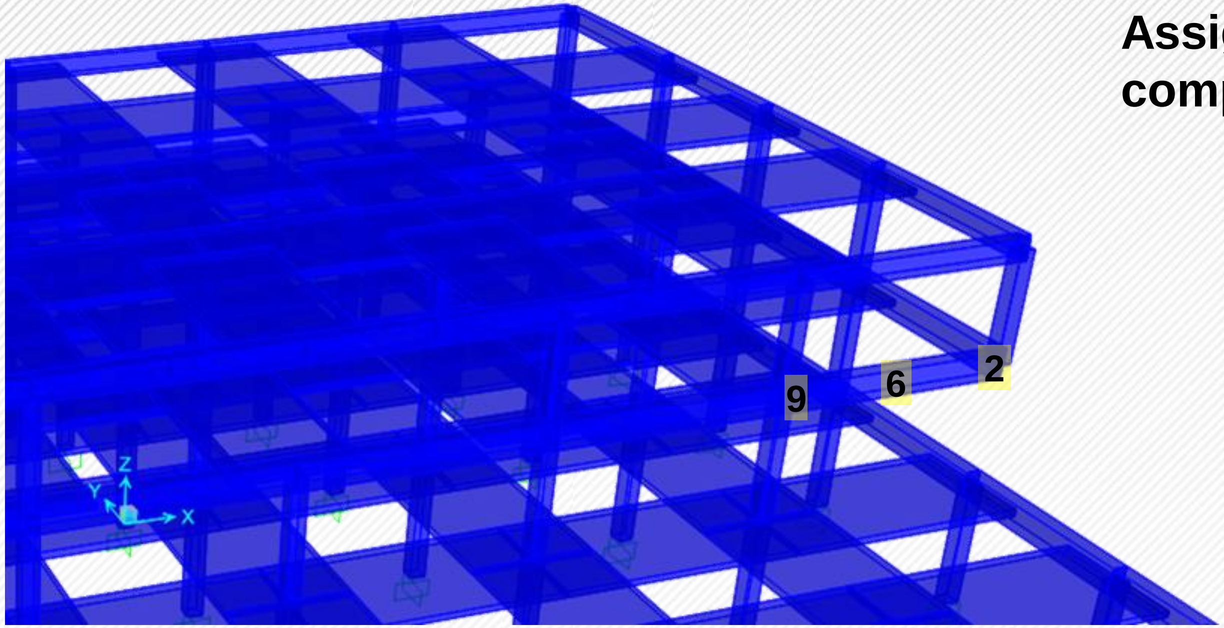


Load Increase Factor – Example



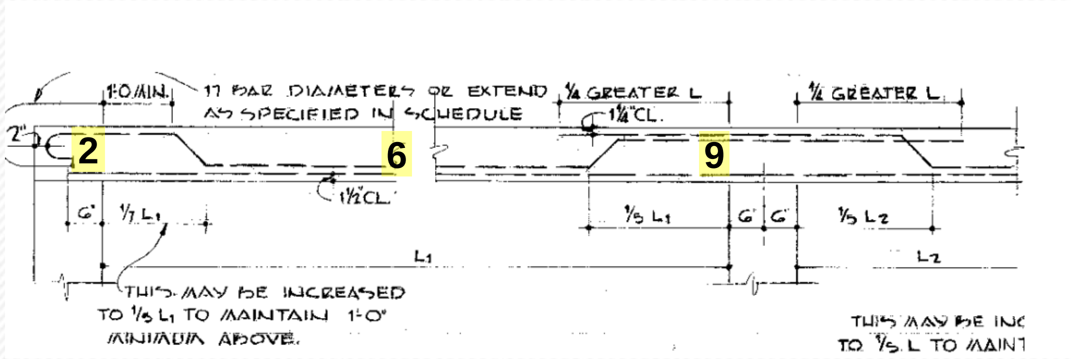
Locations of potential non-linearity within area of load increase

Load Increase Factor – Example



Assign *m* factor at each location within all applicable components using tables from GSA guidelines

Conditions				*m*-factors[1] Component Type Primary	Secondary
i. Beams controlled by flexure[2]					
$\frac{\rho - \rho'}{\rho_{bal}}$	Trans. Reinf.[3]	$\frac{V}{b_w d \sqrt{f'_c}}$ [4]			
≤ 0.0	C	≤ 3		16	19
≤ 0.0	C	≥6		9	9
≥ 0.5	C	≤ 3		9	9
≥ 0.5	C	≥ 6		6	7
≤ 0.0	NC	≤ 3		9	9
≤ 0.0	NC	≥ 6		6	7
≥ 0.5	NC	≤ 3		6	7
≥ 0.5	NC	≥ 6		4	5
ii. Beams controlled by shear[2]					
Stirrup spacing ≤ d /2				1.5	3
Stirrup spacing > d /2				1.5	2
iii. Beams controlled by inadequate development or splicing along the span[2]					
Stirrup spacing ≤ d /2				1.5	3
Stirrup spacing > d /2				1.5	2
iv. Beams controlled by inadequate embedment into beam-column joint[2]					
				2	3



Load Increase Factor – Example

Table 3-4. Load Increase Factors for Linear Static Analysis

Material	Structure Type	Ω_{LD}, Deformation-controlled	Ω_{LF}, Force-controlled
Steel	Framed	$0.9\ m_{LIF} + 1.1$	2.0
Reinforced Concrete	Framed[A]	$1.2\ m_{LIF} + 0.80$	2.0
	Load-bearing Wall	$2.0\ m_{LIF}$	2.0
Masonry	Load-bearing Wall	$2.0\ m_{LIF}$	2.0
Wood	Load-bearing Wall	$2.0\ m_{LIF}$	2.0
Cold-formed Steel	Load-bearing Wall	$2.0\ m_{LIF}$	2.0

[A] Note that, per ASCE 41, reinforced concrete beam-column joints are treated as force-controlled; however, the hinges that form in the beam near the column are deformation-controlled and the appropriate m-factor from Chapter 4 of this UFC shall be applied to the calculation of the deformation-controlled load increase factor Ω_{LD}
\2\

Use smallest *m* to calculate the deformation-controlled LIF (Ω_{LD})

$$\Omega_{LD} = 1.2 \times 2 + 0.8 = 3.2$$

LIF gets applied to PC load case at locations shown next

Linear Static Loading Procedure

- **Covered in § 3-2.11.4**

3-2.11.4.1 **Load Case for Deformation-Controlled Actions Q_{UD}.**

To calculate the deformation-controlled actions, simultaneously apply the following combination of gravity loads:

Increased Gravity Loads for Floor Areas Above Removed Column or Wall. Apply the following increased gravity load combination to those bays immediately adjacent to the removed element and at all floors above the removed element; see Figures 3-13 and 3-14.

\2\ $G_{LD} = \Omega_{LD}\ [1.2\ D + (0.5\ L \text{ or } 0.2\ S)]$ /2/ Equation (3-10)

where
- G_{LD} = Increased gravity loads for deformation-controlled actions for Linear Static Analysis
- D = Dead load including façade loads (lb/ft^2 or kN/m^2)
- L = Live load including live load reduction per Section 3-2.3 (lb/ft^2 or kN/m^2)
- S = Snow load (lb/ft^2 or kN/m^2)
- Ω_{LD} = Load increase factor for calculating deformation-controlled actions for Linear Static analysis; use appropriate value for framed or load-bearing wall structures; see Section 3-2.11.5

Gravity Loads for Floor Areas Away From Removed Column or Wall. Apply the following gravity load combination to those bays not loaded with G_{LD}; see Figures 3-13 and 3-14.

\2\ $G = 1.2\ D + (0.5\ L \text{ or } 0.2\ S)$ /2/ Equation (3-11)

where G = Gravity loads

3-2.11.4.2 **Load Case for Force-Controlled Actions Q_{UF}.**

To calculate the force-controlled actions, simultaneously apply the following combination of gravity loads.

Increased Gravity Loads for Floor Areas Above Removed Column or Wall. Apply the following increased gravity load combination to those bays immediately adjacent to the removed element and at all floors above the removed element; see Figures 3-13 and 3-14.

\2\ $G_{LF} = \Omega_{LF}\ [1.2\ D + (0.5\ L \text{ or } 0.2\ S)]$ /2/ Equation (3-12)

where
- G_{LF} = Increased gravity loads for force-controlled actions for Linear Static analysis
- D = Dead load including façade loads (lb/ft^2 or kN/m^2)
- L = Live load including live load reduction per Section 3-2.3 (lb/ft^2 or kN/m^2)
- S = Snow load (lb/ft^2 or kN/m^2)
- Ω_{LF} = Load increase factor for calculating force-controlled actions for Linear Static analysis; use appropriate value for framed or load-bearing wall structures; see Section 3-2.11.5

Gravity Loads for Floor Areas Away From Removed Column or Wall. Use Equation 3-11 to determine the load **G** and apply as shown in Figures 3-13 and 3-14. \2\/2/

Linear Static Loading Procedure

- **Covered in § 3-2.11.4**
- For floor areas above the removal
  - Deformation-controlled actions

\2\ $G_{LD} = \Omega_{LD}\ [1.2\ D + (0.5\ L \text{ or } 0.2\ S)]$ /2/ Equation (3-10)

  - Force-controlled actions

\2\ $G_{LF} = \Omega_{LF}\ [1.2\ D + (0.5\ L \text{ or } 0.2\ S)]$ /2/ Equation (3-12)

Linear Static Loading Procedure

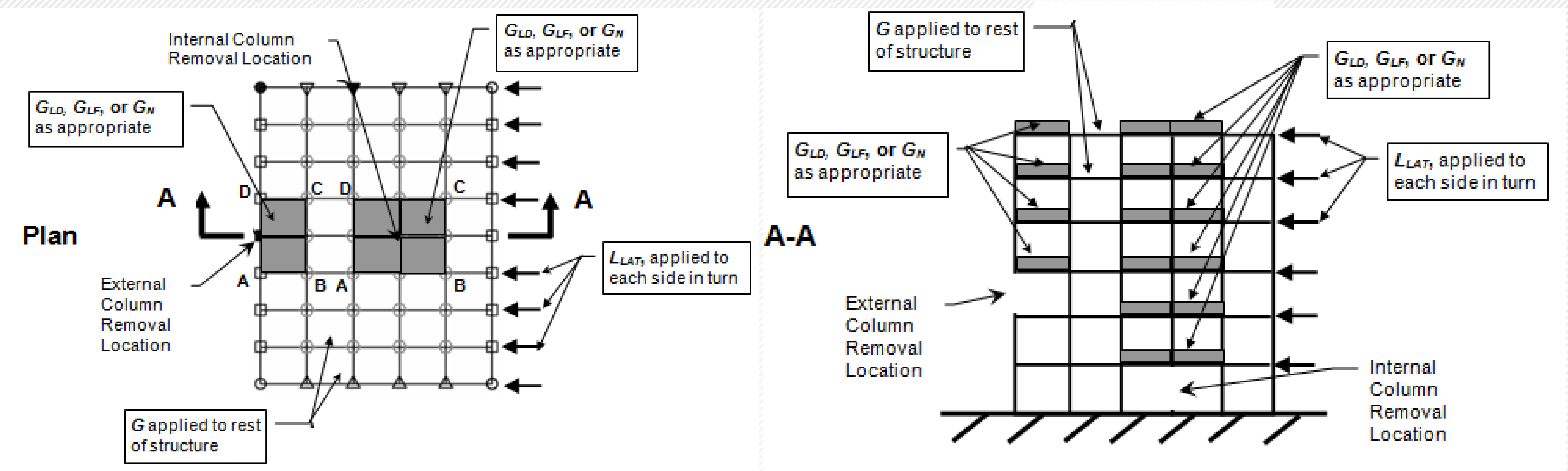


Figure 3-13. Loads and Load Locations for External and Internal Column Removal for Linear and Nonlinear Static Models

Acceptance Criteria

3-2.11.7 Component and Element Acceptance Criteria.

$\Phi\, m\, Q_{CE} \geq Q_{UD}$ Equation 3.6

where Q_{UD} = Deformation-controlled action, from Linear Static model

m = Component or element demand modifier (m-factor) as defined in Chapters 4 to 8 of this document

Φ = Strength reduction factor from the appropriate material specific code

Q_{CE} = Expected strength of the component or element for deformation-controlled actions

For force-controlled actions in all primary and secondary components,

$\Phi\, Q_{CL} \geq Q_{UF}$ Equation 3.7

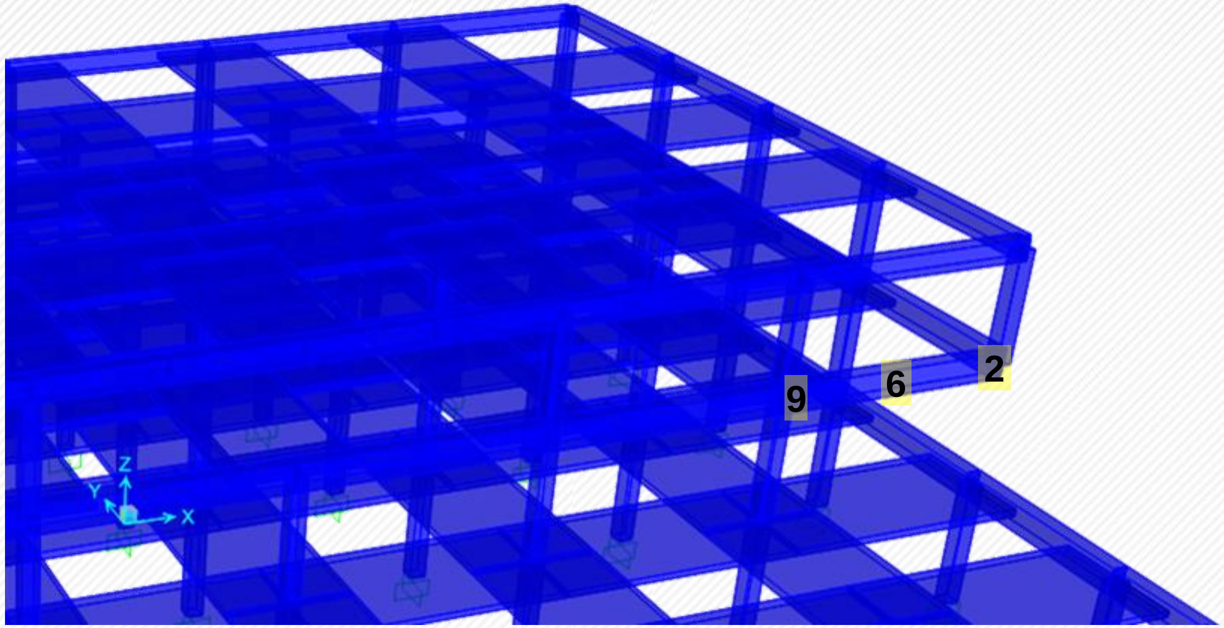
where Q_{UF} = Force-controlled action, from Linear Static model

Q_{CL} = Lower-bound strength of a component or element for force-controlled actions

Φ = Strength reduction factor from the appropriate material specific code

Acceptance Criteria, Example

- Continued from LIF example…



Deformation- Controlled

- $\Omega_{LD} = 1.2 \times 2 + 0.8 = 3.2$ (applied to load case)
- DCRs < 2 – Controlled by beam connection into corner

Force- Controlled

- $\Omega_{LF} = 2$ (applied to load case)
- DCRs < 1

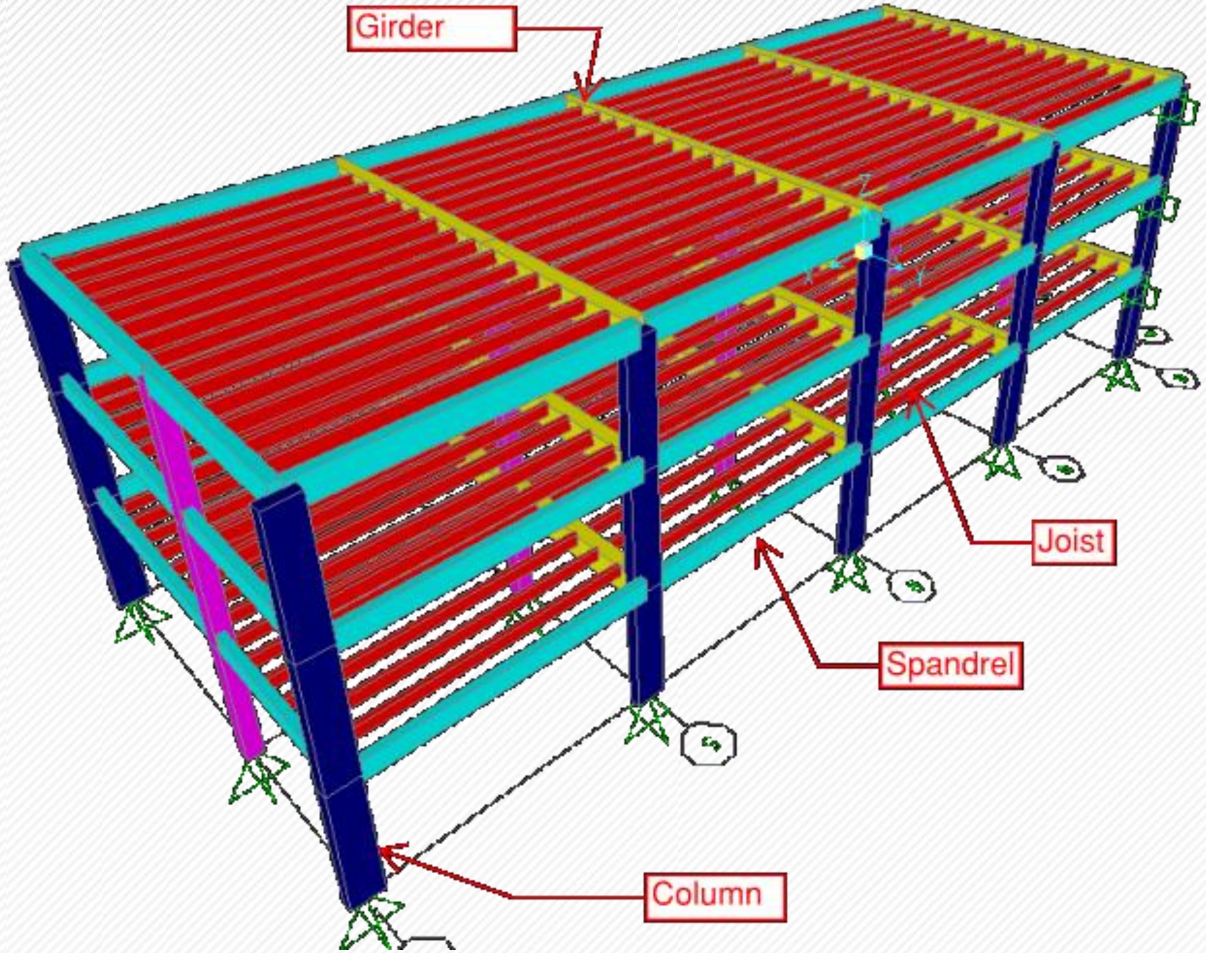
Non-Linear Dynamic Alternate Path Analysis

- **Summarized in § 3-2.13**
- One of three permitted approaches for performing alternate path analysis in GSA guidelines
- Directly accounts for nonlinearity in the structural model (e.g. at defined hinges)
- Most realistic approach to capturing structure performance for load-bearing element removal
- Typically the least conservative analysis method

NLD AP Analysis – Main Steps

1. Develop 3-D model
2. Define modeling parameters and acceptance criteria and incorporate these into your model
3. Define floor loads (LLR permitted)
4. Perform undamaged structure analysis
5. Perform NLD removal analysis
6. Review and interpret results
7. Iterate as required…

NLD Analytical Model

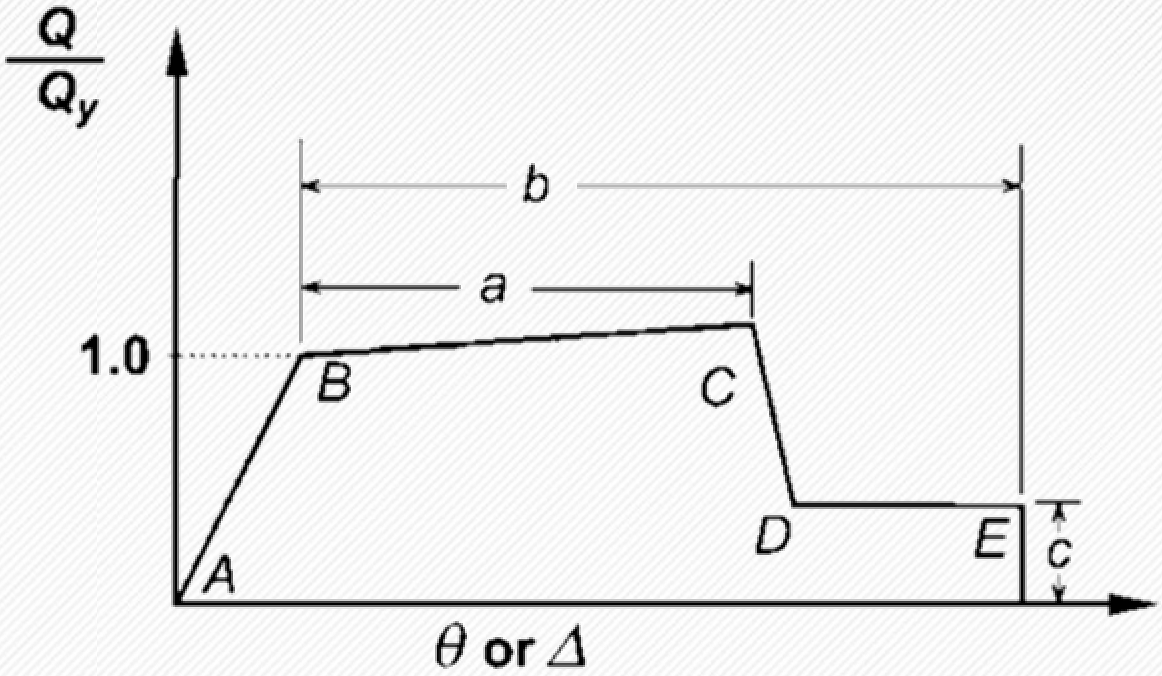


Acceptance Criteria

- **Summarized in § 3-2.13.6.1**
- Deformation-Controlled Actions
  - – Primary and secondary elements and components shall have expected deformation capacities greater than the maximum calculated deformation demands
  - – Expected deformation capacities shall be determined considering all coexisting forces and deformations in accordance with Chapters 4 through 8 of GSA guidelines
    - Material specific chapters

Model Parameters & Acceptance Criteria

- Use ASCE 41 to define model parameters and acceptance criteria **<u>except</u>** where modified by the GSA guidelines
  - For **steel**, use ASCE 41-13 Chapter 9
    - Stiffness per AISC 360
    - Standard hinge curve (this slide)
    - Component-specific guidance in ASCE 41
      - **GSA modifications per § 5-4.3**



Model Parameters & Acceptance Criteria

Partial Table

Based on Reinforcing Ratios Loads and Component Types

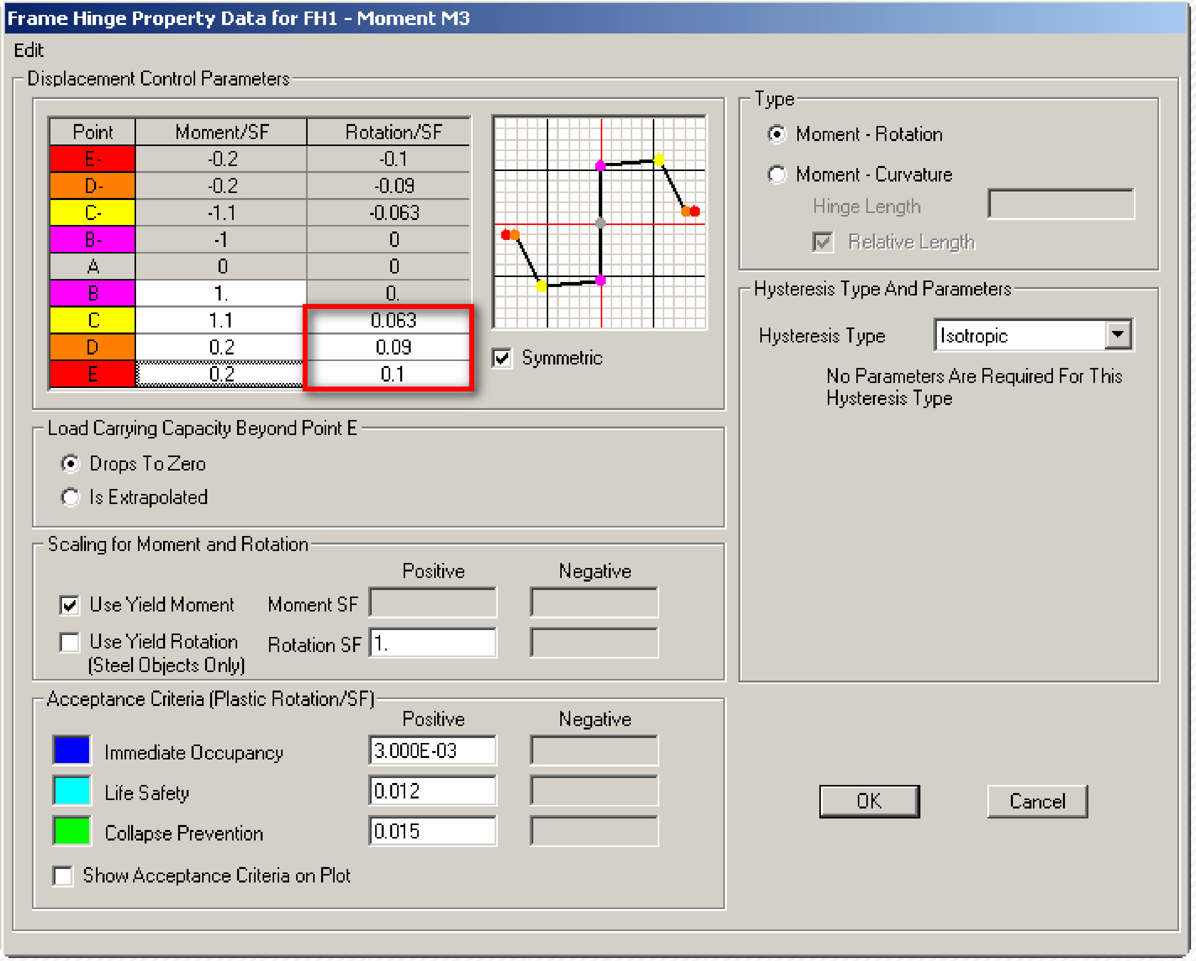
Table 6. Nonlinear Modeling Parameters and Acceptance Criteria for Reinforced Concrete Beams (Replacement for Table 10-7 in ASCE 41)

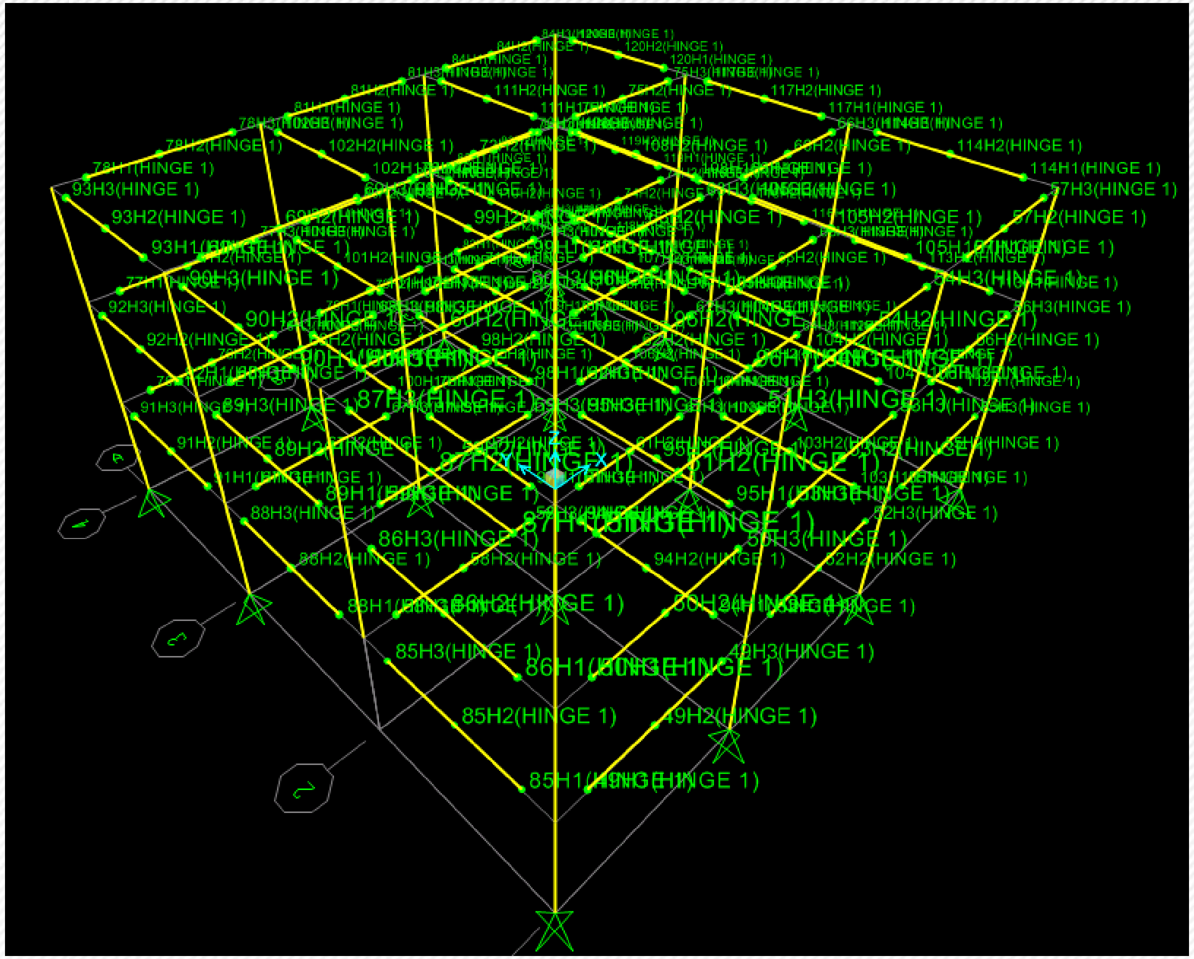
Conditions			Modeling Parameters[1]			Acceptance Criteria[1,2]
			Plastic Rotations Angle, radians		Residual Strength Ratio	Plastic Rotations Angle, radians
			a	b	c	
i. Beams controlled by flexure[3]						
$\frac{\rho - \rho'}{\rho_{bal}}$	Trans. Reinf.[4]	$\frac{V}{b_w d \sqrt{f'_c}}$ [5]				
$\leq$ 0.0	C	$\leq$ 3	0.063	0.1	0.2	0.1
$\leq$ 0.0	C	$\geq$ 6	0.05	0.08	0.2	0.08
$\geq$ 0.5	C	$\leq$ 3	0.05	0.06	0.2	0.06
$\geq$ 0.5	C	$\geq$ 6	0.038	0.04	0.2	0.04
$\leq$ 0.0	NC	$\leq$ 3	0.05	0.06	0.2	0.06
$\leq$ 0.0	NC	$\geq$ 6	0.025	0.03	0.2	0.03
$\geq$ 0.5	NC	$\leq$ 3	0.025	0.03	0.2	0.03
$\geq$ 0.5	NC	$\geq$ 6	0.013	0.02	0.2	0.02
ii. Beams controlled by shear[3]						
Stirrup spacing $\leq$ d/2			0.003	0.02	0.2	0.02
Stirrup spacing > d/2			0.003	0.01	0.2	0.01
iii. Beams controlled by inadequate development or splicing along the span[3]						
Stirrup spacing $\leq$ d/2			0.003	0.02	0	0.02
Stirrup spacing > d/2			0.003	0.01	0	0.01
iv. Beams controlled by inadequate embedment into beam-column joint[3]						
			0.015	0.03	0.2	0.03

Example where GSA supersedes ASCE41

Refer to material chapters to determine which modeling parameters and acceptance criteria to use

Modeling Parameters & Acceptance Criteria





Loads for NLD Analysis

- Similar to LS approach without dynamic factors
  - No higher loaded region at removal to account for dynamic effects (captured explicitly in NLD analysis)
- Similar to ASCE7-10 extraordinary event load combination

Gravity Loads for Entire Structure. Apply the gravity load combination in Equation 3.11 to the entire structure.

$$G_{ND} = 1.2\,D + (0.5\,L \text{ or } 0.2\,S) \qquad \text{Equation 3.11}$$

where G_{ND} = Gravity loads for Nonlinear Dynamic Analysis

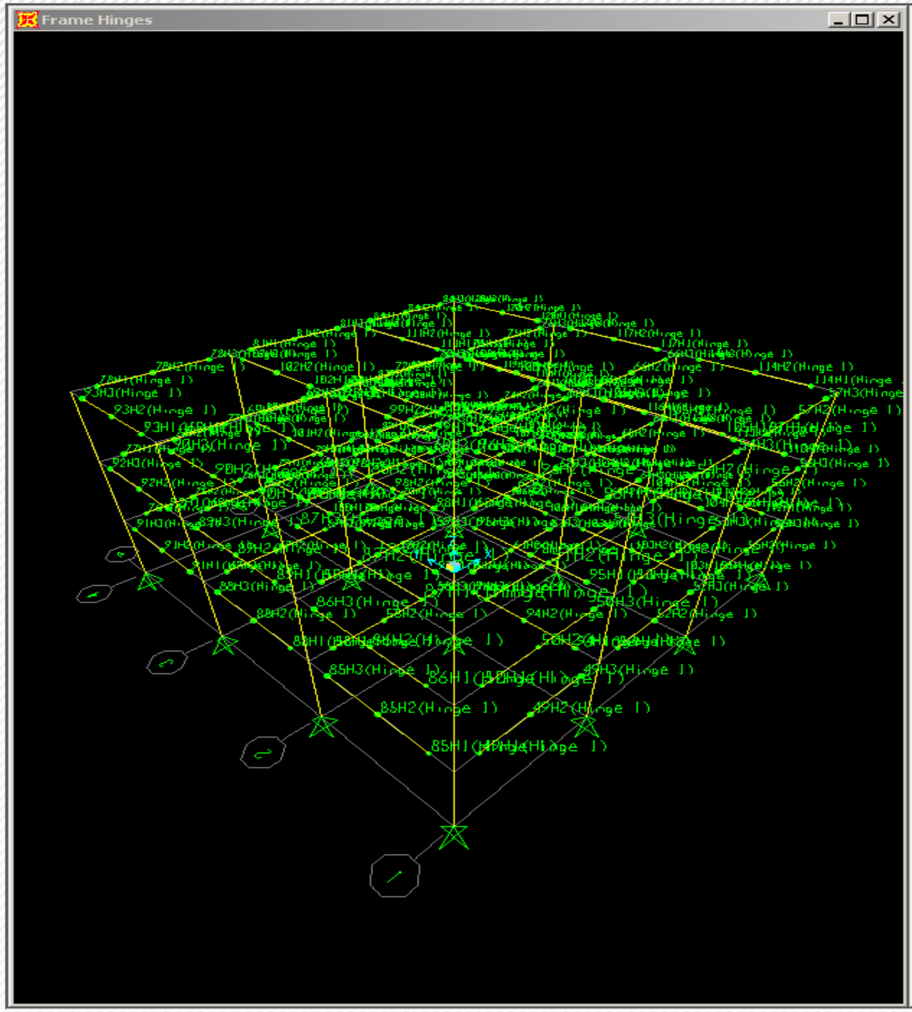
D = Dead load including façade loads (lb/ft^2 or kN/m^2)

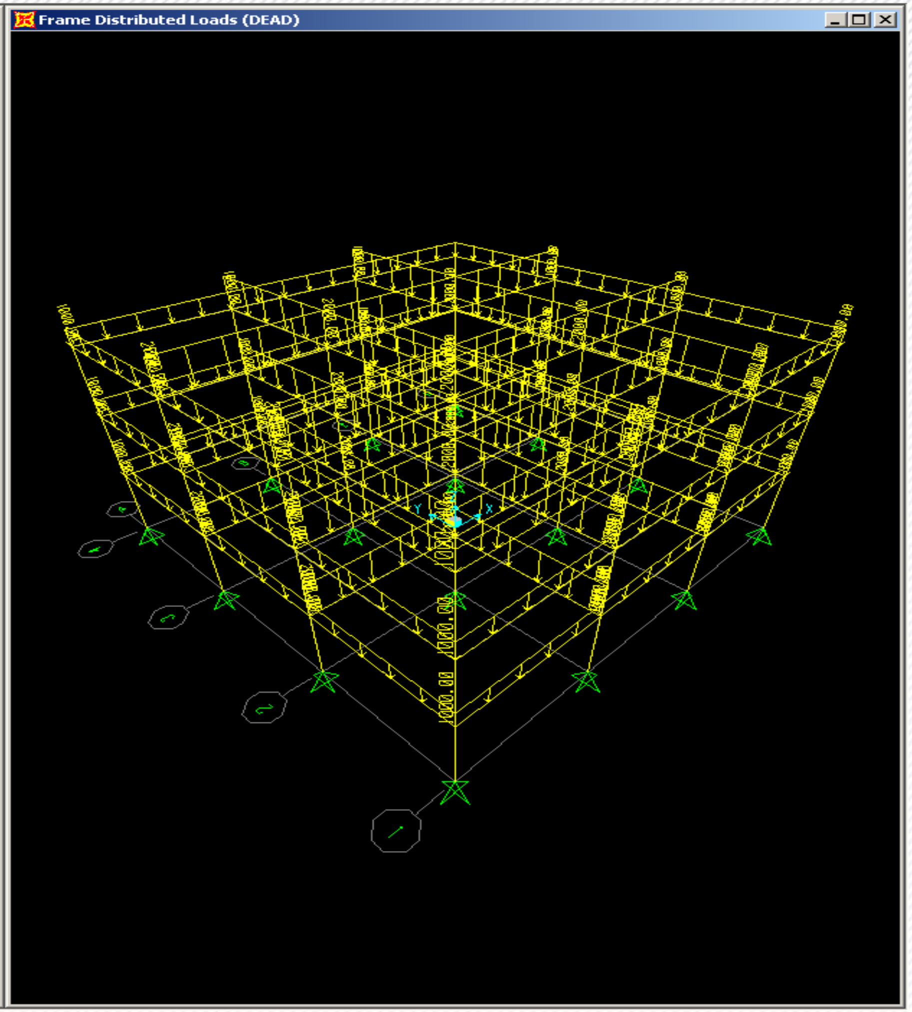
L = Live load including live load reduction per Section 3.2.3, not to exceed 50-lb/ft^2 or 244-kN/m^2

S = Snow load (lb/ft^2 or kN/m^2)

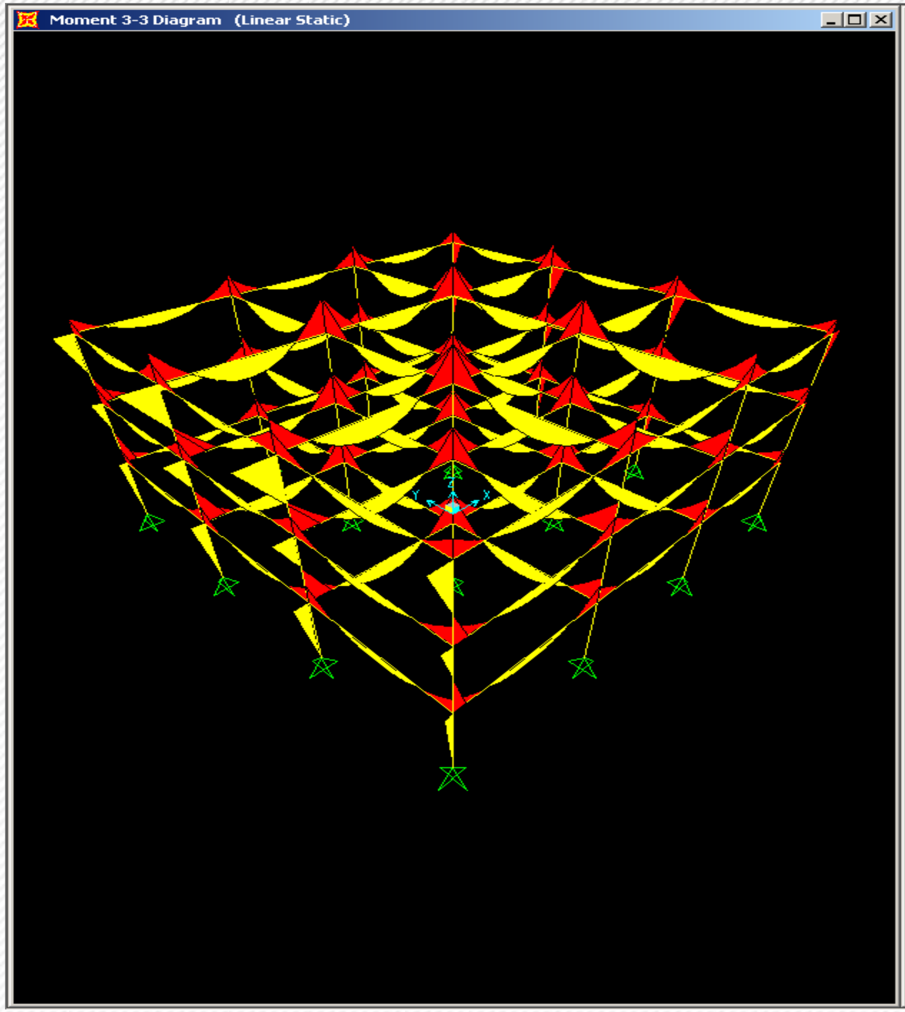
Gravity only
No lateral loads

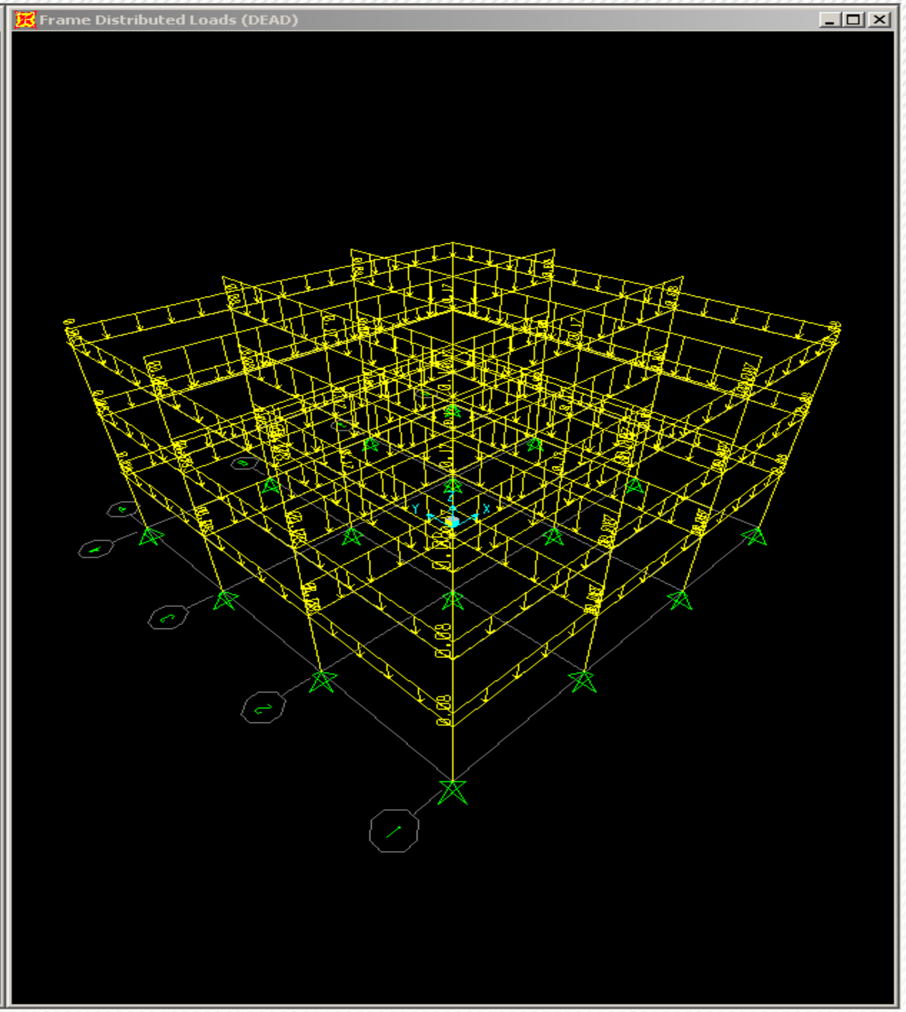
Apply Loads





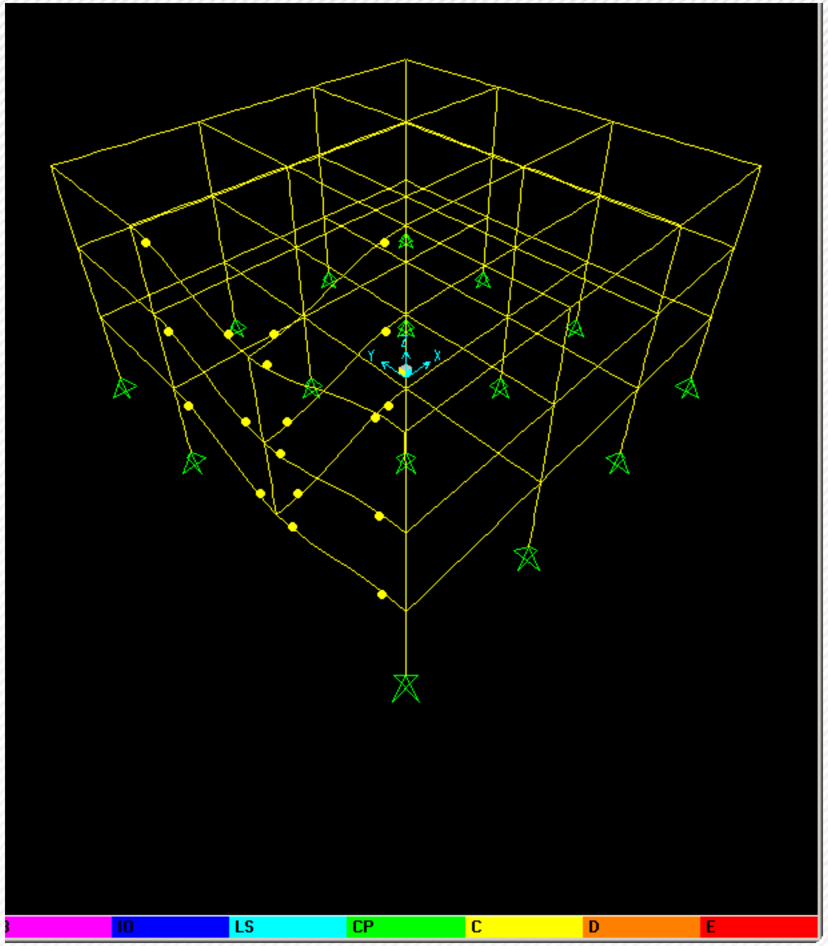
Undamaged Structure Analysis





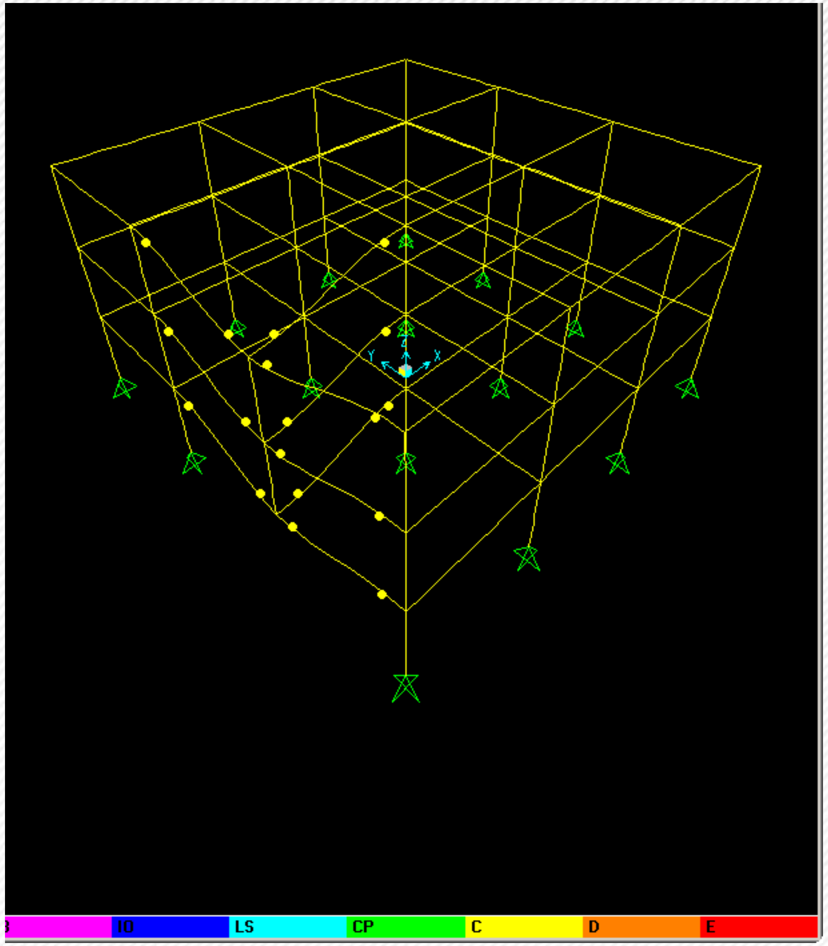
NLD Analysis

- Ensure non-linearities are defined
- Ensure P-Δ is captured
- Ensure analysis is dynamic
- Run your model
  - Analyze until at least one full cycle of vertical motion is reached
  - 2+ is better, especially if the model captures aggregating damage



NLD Analysis

- Since this is a dynamic analysis case, it is important to capture the dynamic properties accurately and conservatively
  - **Strength / Stiffness**
    - Per UFC and ASCE 41
  - **Damping**
    - ASCE41 recommends < 3% for NLD
    - See ASCE41-13 § 7.2.3.6
  - **Mass**
    - Use loads and self-weights to define mass
    - **Take care not to double count mass**



GSA and VA (Existing Facilities)

THREAT DEPENDENT APPROACH

Threat Dependent Approach, Cont'd

- Use in combination with GSA Interpretation document
- Perform blast analysis in accordance with GSA guidelines
- Show element will not "fail" against specific threat
- Must be approved by GSA technical SME

Clarification for application of Threat Dependent Approach - Table 15, provides additional requirements for implementation of the Threat Dependent Approach per section 1.2.2 in the GSA Alternate Path and Design Guidelines for Progressive Collapse Resistance.

Table 15 Requirements for Threat Dependent Approach for Progressive Collapse Resistance

Building Type	FSL III	FSL IV
New and Existing Building	For new and existing buildings, if an exterior column, a column in underbuilding parking, or a column in unscreened areas is shown to meet the level of protection described in section 3.2.6 for an FSL IV Building against the applicable DBT (section 2.2.2), progressive collapse design in compliance with the GSA Alternate Path and Design Guidelines for Progressive Collapse Resistance is not required for the specific column.	For new and existing buildings, if an exterior column, a column in underbuilding parking, or a column in unscreened areas is shown to meet the level of protection described in section 3.2.6 for as FSL IV Building against the applicable DBT (section 2.2.2), progressive collapse design in compliance with the GSA Alternate Path and Design Guidelines for Progressive Collapse Resistance is not required for the specific column.

3.2.6 BLAST RESISTANCE – FAÇADE AND STRUCTURE

[This section is not found in ASCE 59]

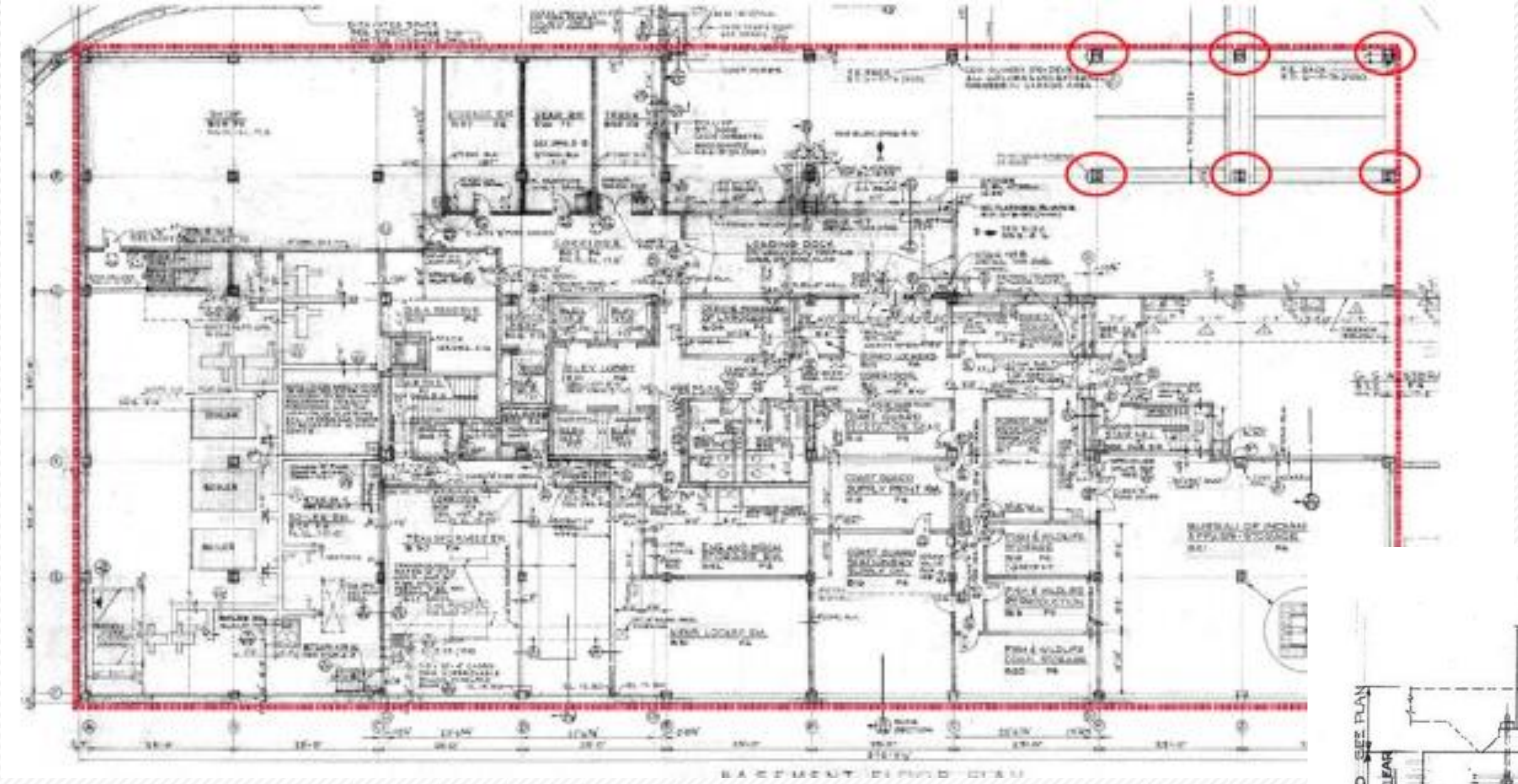
3.2.6.1 FSL III REQUIREMENTS

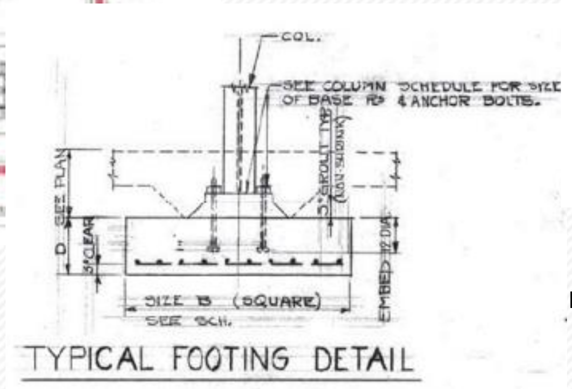
For GSA projects, the following minimum requirements apply to façade and structure components.

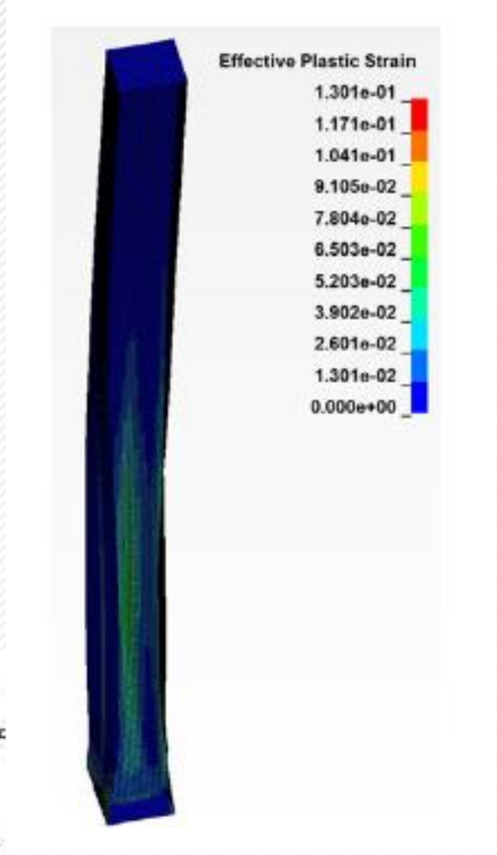
Table 9 Blast-resistant Design Requirements for Blast-resistant Façade and Structure in FSL III Facilities

Facility Security Level (FSL)	Member type	Response Criteria	Applicable Threats and Blast Loads	Methods of Analysis and Design Requirements
FSL III	Primary Members	Moderate Damage per Section 3.4 and Breach per Section 3.4.4	Per Section 2.2.2, and Chapter 4 (External blast loads)	Per applicable sections of Chapters 6 and 8
	Secondary Members	Heavy Damage per Section 3.4		

Threat Dependent Approach – Example



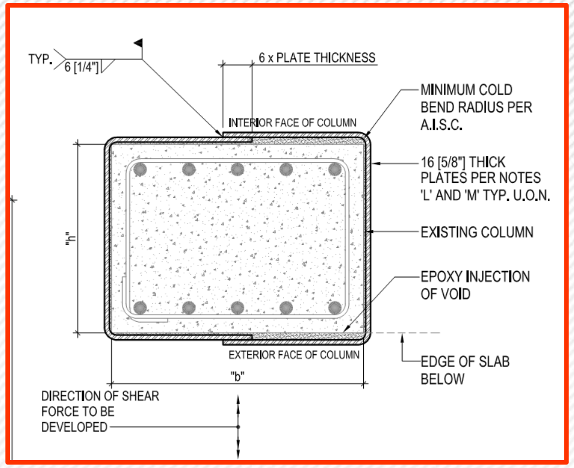


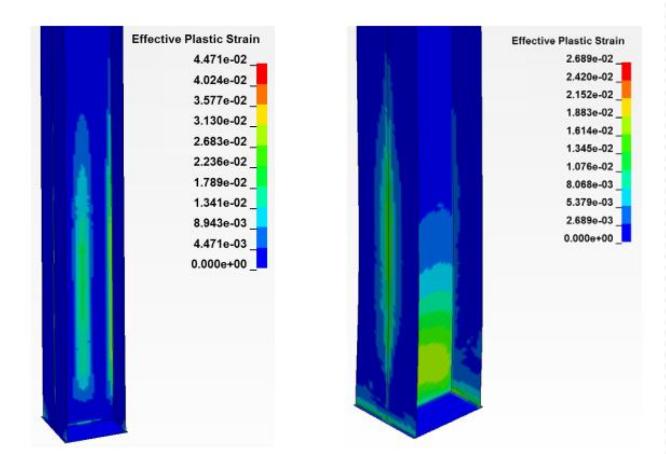


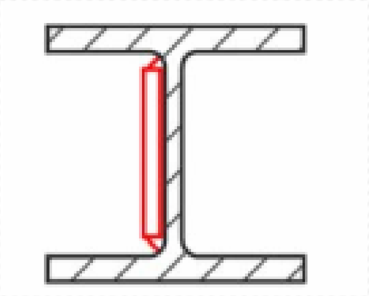
High Fidelity FEA Blast Analysis of Screen VBIED next to column – Meets Moderate Damage definition (Adequate for Mitigation of PC)

Retrofits – Threat Dependent Approach

- Threat Dependent Approach
- Localized retrofits
  - Easier to install
  - Generally lower cost
- Typically improve connection strength and brittle failure modes







Summary

- Progressive Collapse mitigation is required for
  - DoD new buildings with 3 stories or more
  - Veteran affairs (VA) buildings with 3 stories or more
  - GSA buildings with 4 stories or more
- Design Guidance
  - UFC 4-023-03 (DoD and Referenced by VA)
  - GSA Alternate Path Guidelines (Based on UFC 4-023-03 with modifications)
- Tie Forces
  - Uses additional tension members to improve redundancy and continuity
  - Distribute forces from damaged to undamaged areas
- Alternate Path analysis
  - Explicit removal of selected load-bearing elements
  - Approached based on DoD UFC 4-023-03 with modifications
  - Redundancy requirement to spread out PC resisting system
- Threat-dependent approach
  - Protection is provided by preventing failure of vulnerable elements
  - Preferred for existing buildings

Thank you!

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