Brian Rose

AE Senior Thesis Presentation

General Office Building

Structural Option
Faculty Consultant:
Dr. Boothby

Presentation Outline

- Introduction

Base Steel Redesign

Progressive Collapse

- Tie Force
- Alternative Path
- Enhanced Local Resistance

Architectural Breadth

Conclusions

Introduction

Project Location

Headquarters Expansion
Greater Washington, D.C. Area

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120,000 SF

10 Stories (90ft)

$40 Million

Aug. 2010 – Dec.2011

Project Team

Owner: Health Research

Architect & Engineer: EWING COLE

General Contractor: DPR Construction Inc.

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Existing Structure

Two-Way Flat Slab

22’x20’ Bays

Drop Panels

Shear Wall Cores

Spread Footings

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Proposed Redesign Depth

Progressive Collapse

ASCE 7 Definition:

"The spread of an initial local failure from element to element, eventually resulting in the collapse of an entire structure or a disproportionately large part of it"

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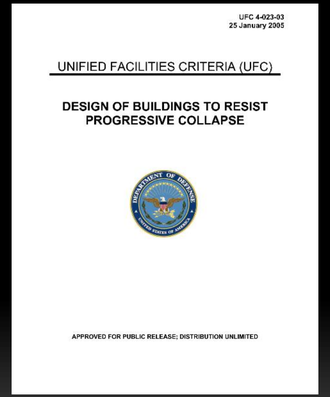

UFC 4-023-03
25 January 2005

UNIFIED FACILITIES CRITERIA (UFC)

DESIGN OF BUILDINGS TO RESIST PROGRESSIVE COLLAPSE

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

Proposed Redesign Depth

Goals

- Design to UFC criteria
- Explore impacts of this analysis
- Minimal architectural impact

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Proposed Redesign Breadths

Architecture

Structural Impacts

Atrium Façade

Site Plan

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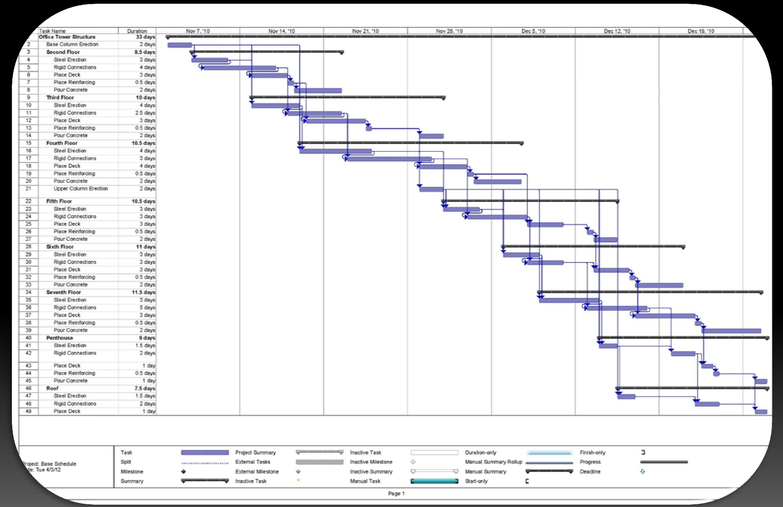

Proposed Redesign Breadths

Architecture

Structural Impacts

Atrium Façade

Site Plan

Construction Management

Cost

Schedule

Presentation Outline

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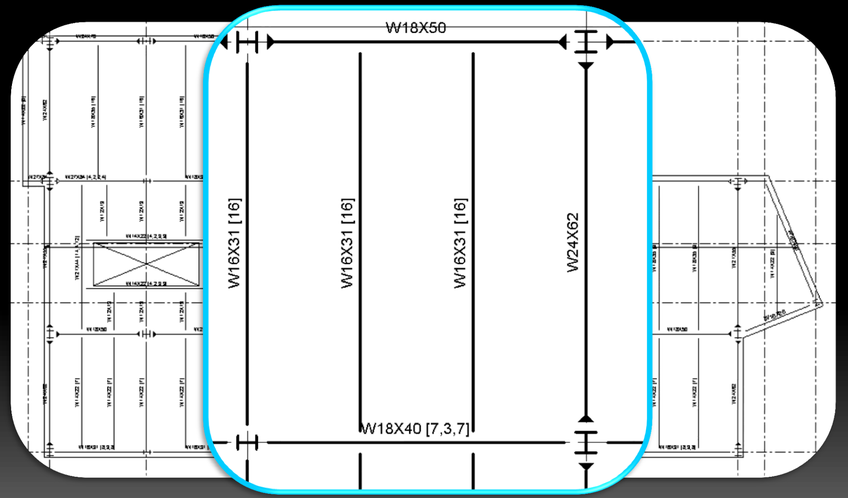
Base Steel Redesign



Gravity System

Results

Typical Infill Beam: W16x31 [16]
Typical Girder: w18x40 [7,3,7]

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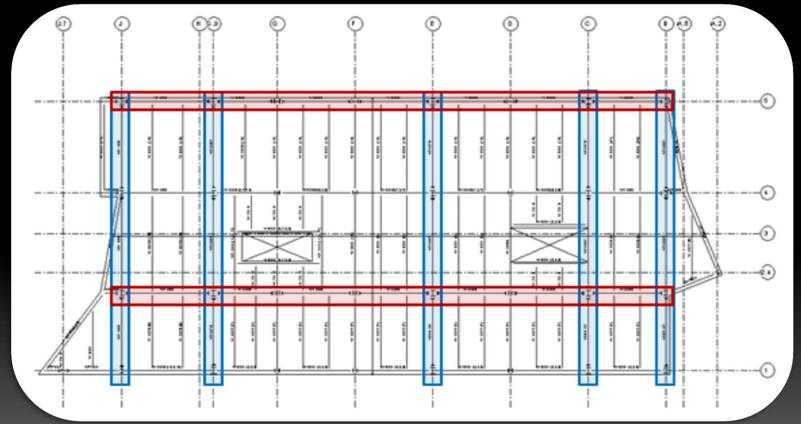
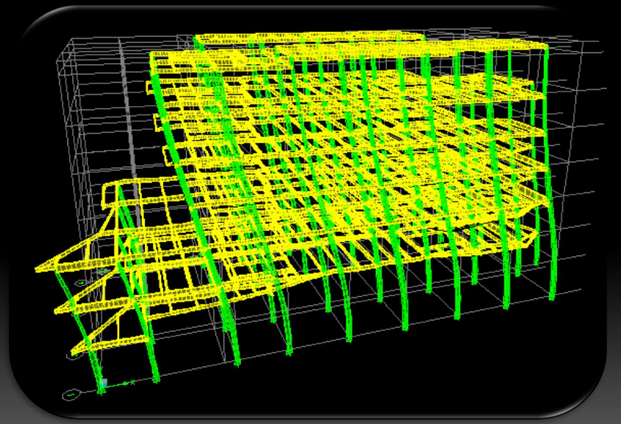
Base Steel Redesign

Moment Frame Location



Lateral System

ETABS Computer Model



Presentation Outline

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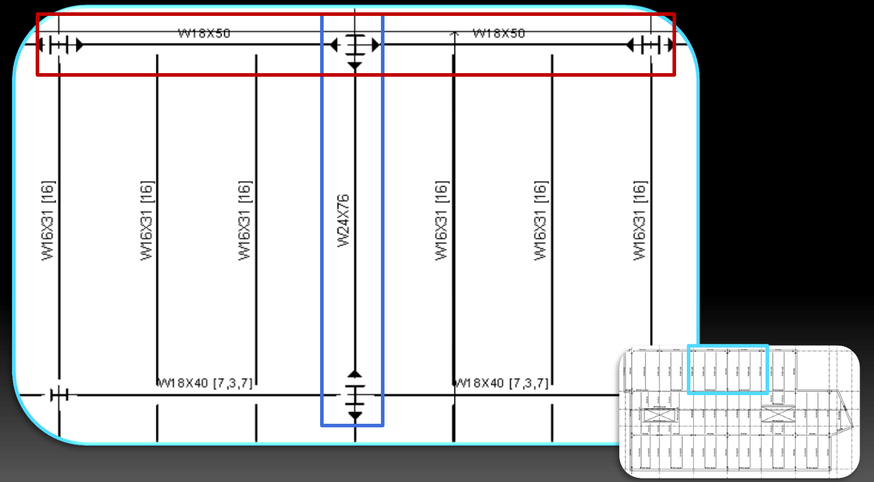
Base Steel Redesign



Lateral System

Results

Table 4.2: Frame Sizes

	Typical Lower Column	Typical Upper Column	Typical 2nd Floor Beam	Typical 3rd Floor Beam	Typical 4th+ Floor Beam
North-South Frames (C, E, & G.9)	W14x233	W14x233	W36x182	W30x108	W24x76
North-South Frames (B & J)	W14x211	W14x145	W36x182	W30x108	W24x76
East West Frames (2&5)	W14x176	W14x176	W18x50	W18x50	W18x50
Gravity Columns	W14x132	W14x82	---	---	---

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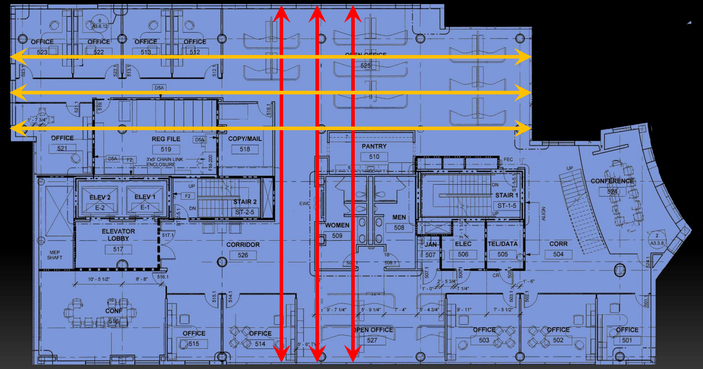
Progressive Collapse

UFC 4-023: Design Requirements



Tie Force Analysis

Longitudinal Ties
#4 @ 12" O.C.
Transverse Ties
#4 @ 13" O.C.

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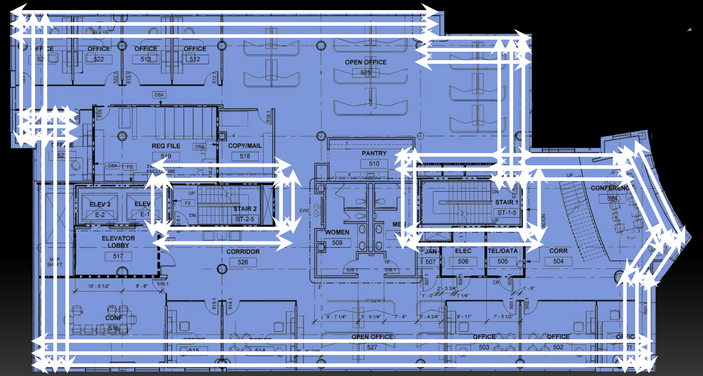
UFC 4-023: Design Requirements



Tie Force Analysis

Longitudinal Ties
#4 @ 12" O.C.
Transverse Ties
#4 @ 13" O.C.
Peripheral Ties
(4) #6 in 3'-0" section

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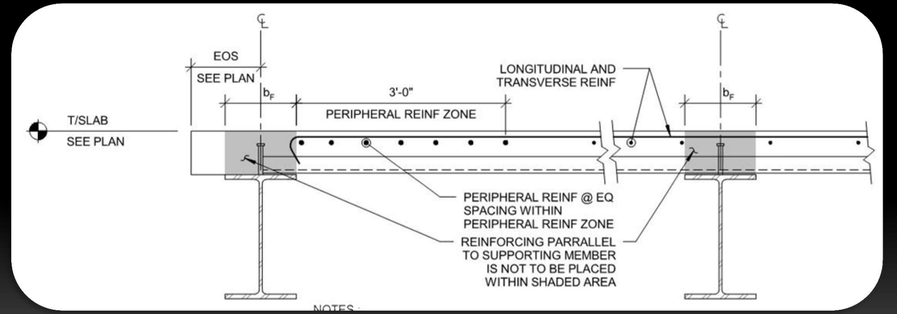

Tie Force Analysis

Detailing

Seismic Hooks

Presentation Outline

Introduction
Base Steel Redesign
Progressive Collapse
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UFC 4-023: Design Example

Alternative Path Analysis

UFC 023: "determine if the structure can bridge over the deficient element after it has been notionally removed"

Linear Static Method

Presentation Outline

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Base Steel Redesign
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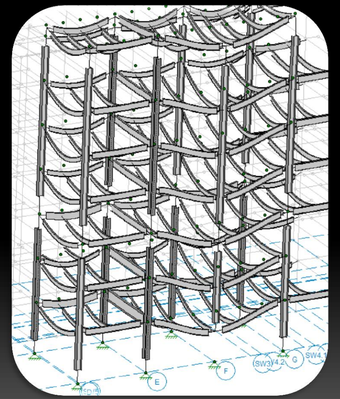
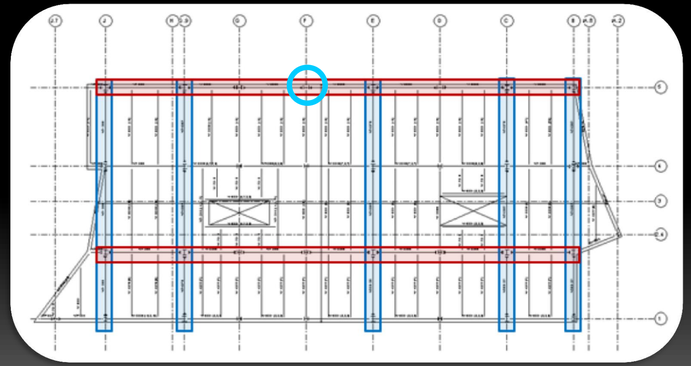
Progressive Collapse

Isometric of Area Near Removed Column



Alternative Path Analysis

Second Floor Framing Plan



Presentation Outline

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UFC 4-023: Typical Action Classifications

Component	Deformation-Controlled Action	Force- Controlled Action
Moment Frames • Beams • Columns • Joints	 Moment (M) M --	 Shear (V) Axial load (P), V V[1]
Shear Walls	M, V	P
Braced Frames • Braces • Beams • Columns • Shear Link	 P -- -- V	 -- P P P, M
Connections	P, V, M[2]	P, V, M

Alternative Path Analysis

Linear Static Method

M-factors

ASCE 41 definition:
"non-linear deformation capacities"

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Shear Walls	M, V	P
Braced Frames • Braces • Beams • Columns • Shear Link	 P -- -- V	 -- P P P, M
Connections	P, V, M[2]	P, V, M

Alternative Path Analysis

Interaction Equation

Moment Divided by m-factor
Expected Strengths Used
Typical Frames = 6

$$\frac{Pr}{\Omega * Pc} + \frac{\frac{8}{9}\left[\frac{Mrx}{\Omega * Mcx} + \frac{Mry}{\Omega * Mcy}\right]}{m - factor}$$

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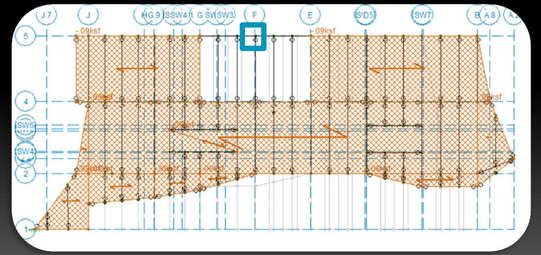
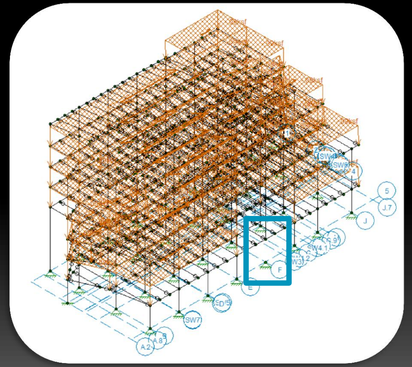
UFC 4-023: Far Load Combination

$$(0.9 \text{ or } 1.2)D + (0.5L \text{ or } 0.2S) + 0.002\Sigma P$$



Alternative Path Analysis

Isometric of Far Loads



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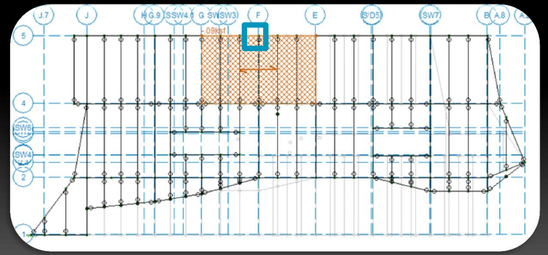
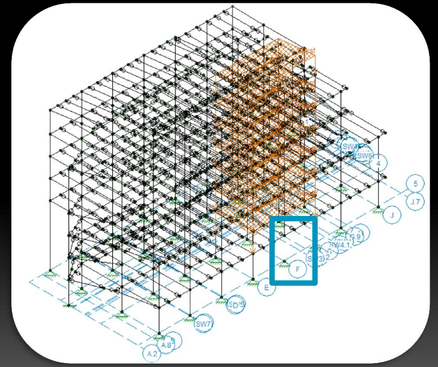
UFC 4-023: Near Load Combination

$$\Omega[(0.9 \text{ or } 1.2)D + (0.5L \text{ or } 0.2S)] + 0.002\Sigma P$$



Alternative Path Analysis

Isometric of Far Loads



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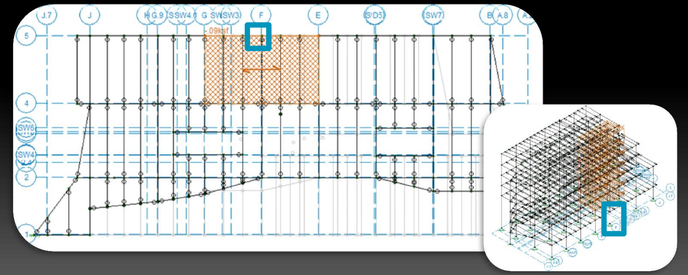
$$\Omega[(0.9 \text{ or } 1.2)D + (0.5L \text{ or } 0.2S)] + 0.002\Sigma P$$



Alternative Path Analysis

Force Controlled Actions:

$\Omega_{LF} = 2.0$

Deflection Controlled Actions:

$\Omega_{LD} = 0.9m_{LIF}+1.1$

m_{LIF} : smallest m-factor of adjacent elements

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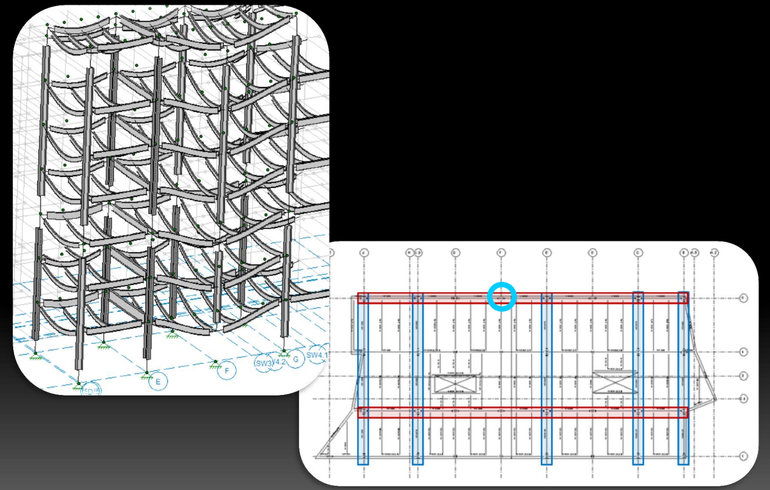
Results

Frame Sizes That Pass Removal of Column F5 Scenario			
	Typical Lower Column	Typical Upper Column	Typical 4th+ Floor Beam
North-South Frames (C, E, & G.9)	W14x370	W14x370	W24x76
North-South Frames (B & J)	W14x370	W14x370	W24x76
East West Frames (1&5)	W14x370	W14x370	W21x68
East West Frames (2)	W14x370	W14x370	W18x50
Gravity Columns	W14x132	W14x82	---

Alternative Path Analysis



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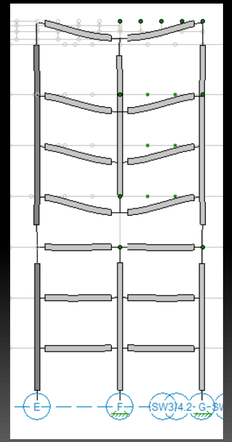
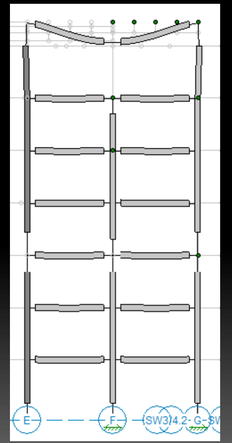
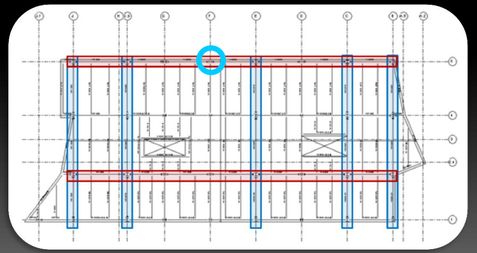
Removal at 4th Floor | Removal at 7th Floor





Alternative Path Analysis



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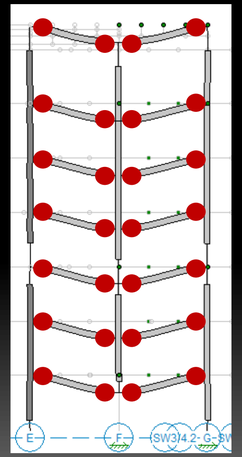
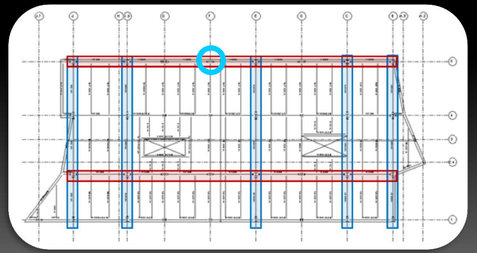
Nonlinear Hand Calculations



Alternative Path Analysis

Linear Static Results: w21x68
Nonlinear Results: W21x62



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RAM Connection: Moment Connection

Alternative Path Analysis

Results:

Full Penetration Welds
(6) 1" dia. A325N Bolts

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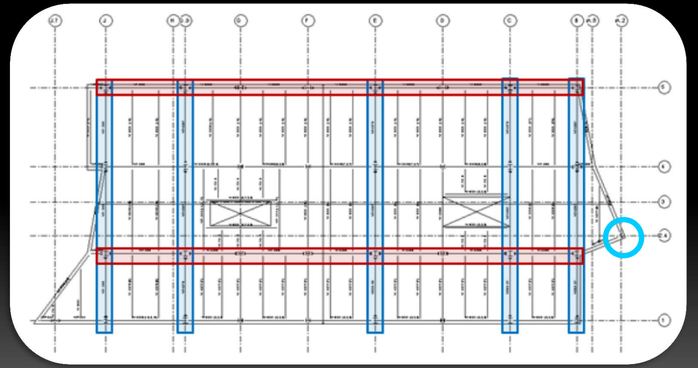
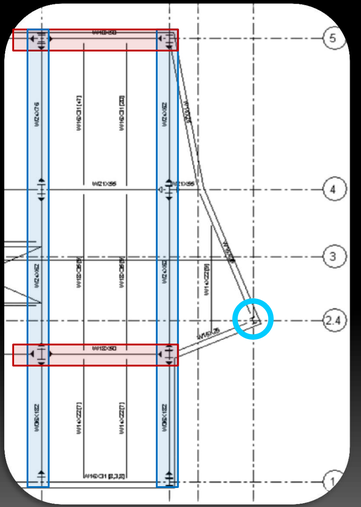
West Façade Column



Alternative Path Analysis



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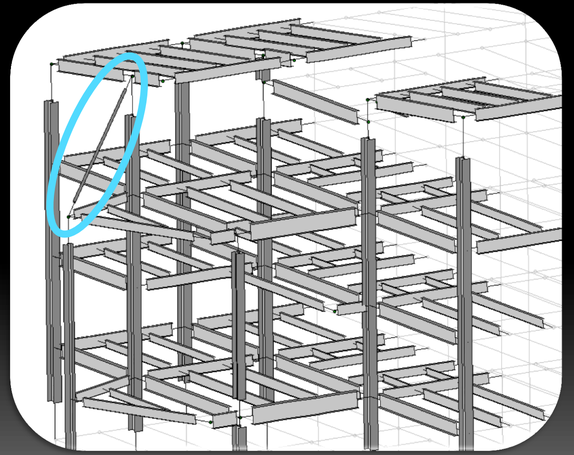
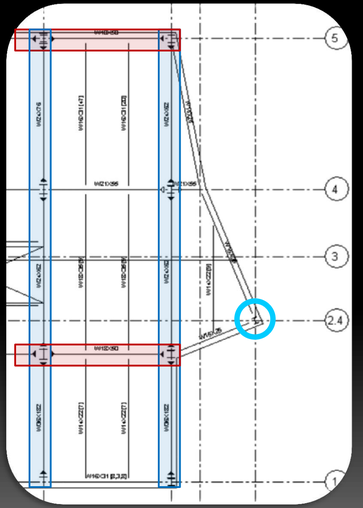


Alternative Path Analysis



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Progressive Collapse

Atrium Curtain Wall

Alternative Path Analysis

Floor Plan

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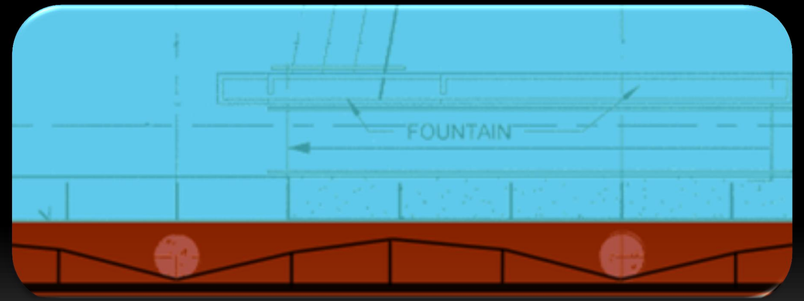
Atrium Curtain Wall Plan



Alternative Path Analysis

Results

½" Cable
20" Sag at Midspan

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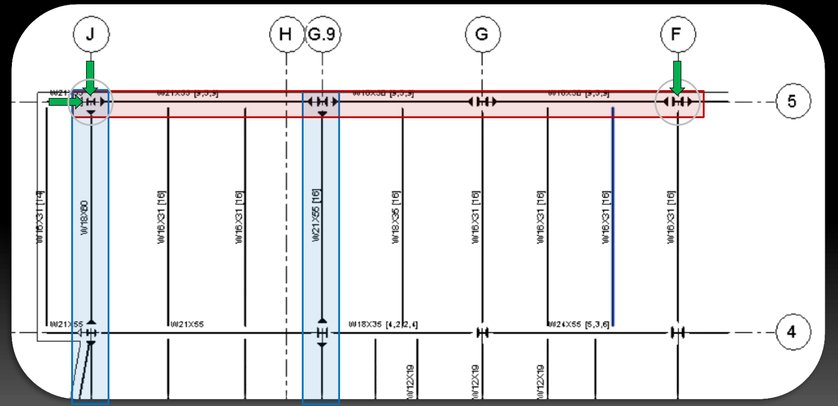
Nonlinear Hand Calculations



Enhanced Local Resistance

Lateral Load Causes Flexural Failure

Corner Column Results

7/16" Doubler Plate

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- **Architectural Breadth**

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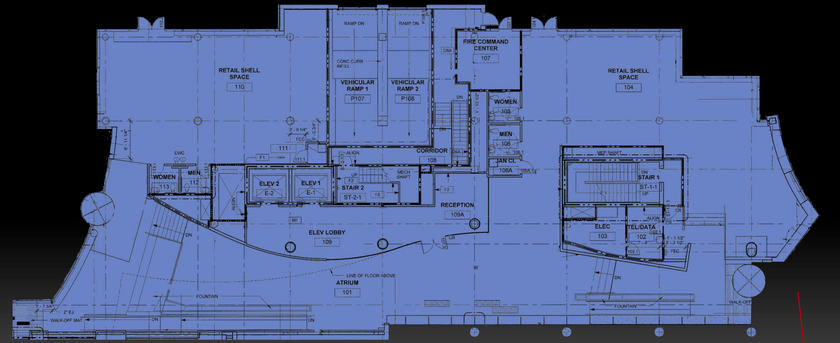
Architecture Breadth

Existing Exterior Atrium View

Atrium Curtain Wall

Existing First Floor Plan



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- **Architectural Breadth**

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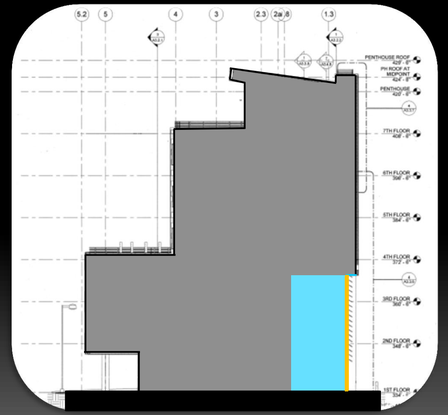
Architecture Breadth

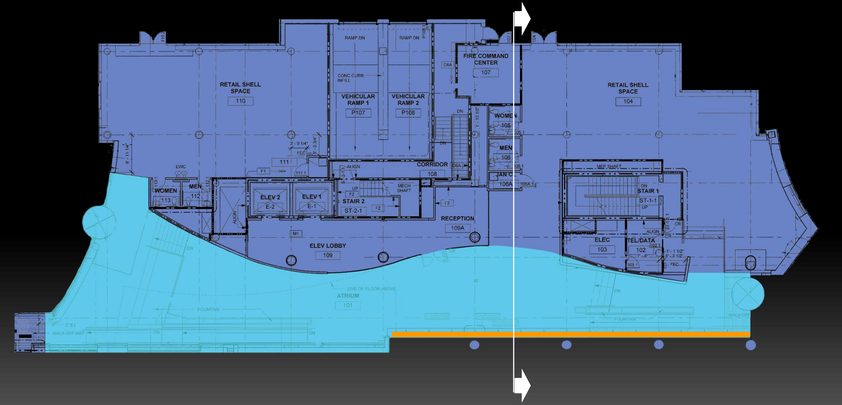
Existing Atrium Section



Atrium Curtain Wall

Existing First Floor Plan

Atrium Highlighted



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Progressive Collapse

Atrium Curtain Wall

Alternative Path Analysis

Floor Plan

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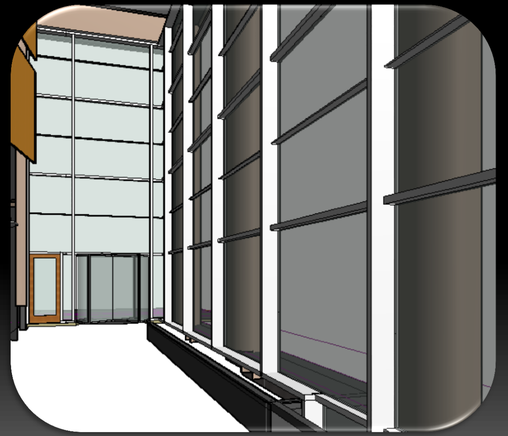
- **Architectural Breadth**
- Conclusions

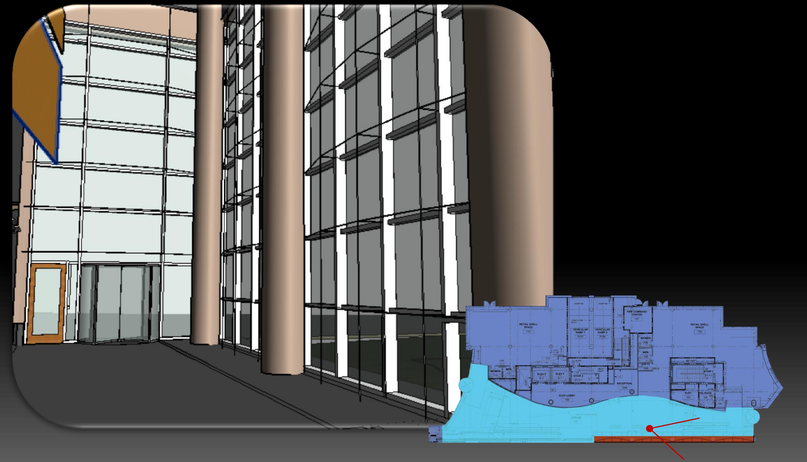
Architecture Breadth

Existing Interior Atrium View



Atrium Curtain Wall

Redesigned Interior Atrium View



Presentation Outline

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- Progressive Collapse
  - Tie Force
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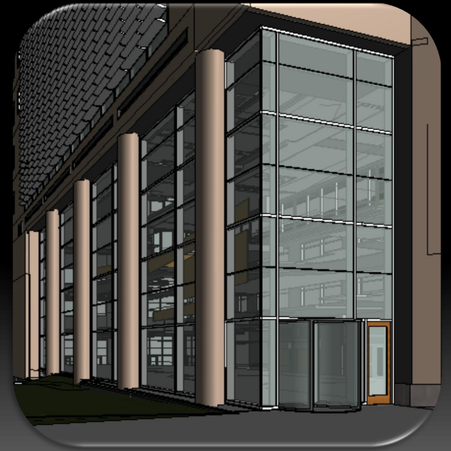
- **Architectural Breadth**
- Conclusions

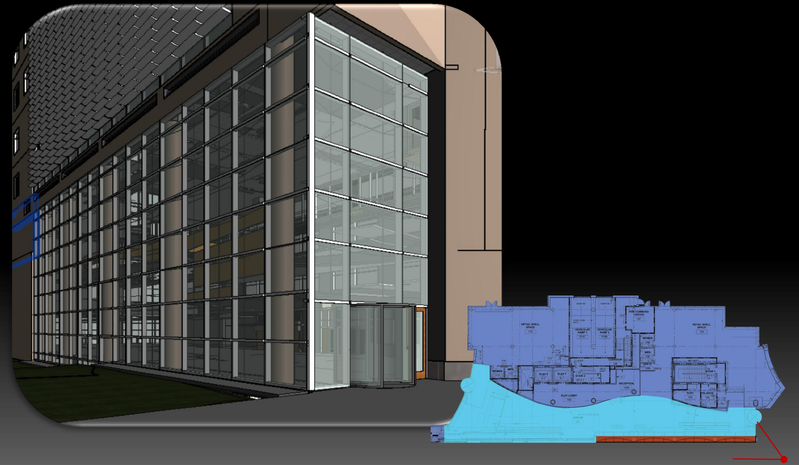
Architecture Breadth

Existing Interior Atrium View



Atrium Curtain Wall

Redesigned Interior Atrium View



Presentation Outline

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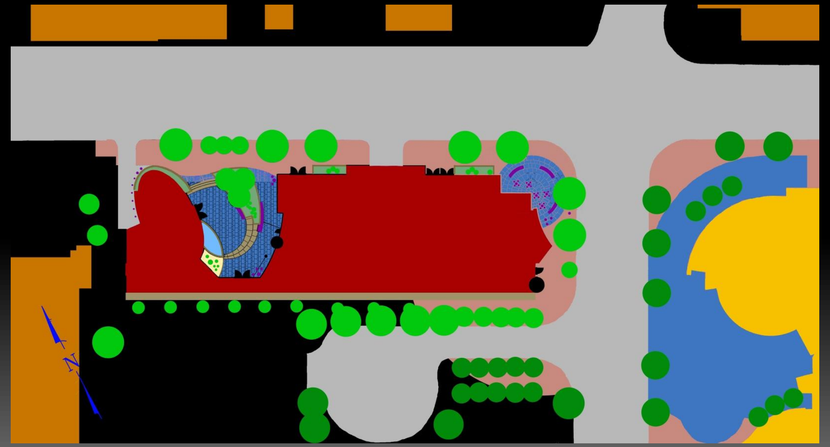
- Enhanced Local Resistance

- **Architectural Breadth**

Conclusions

Architecture Breadth

Existing Site Plan



Site Redesign

Existing Project Location

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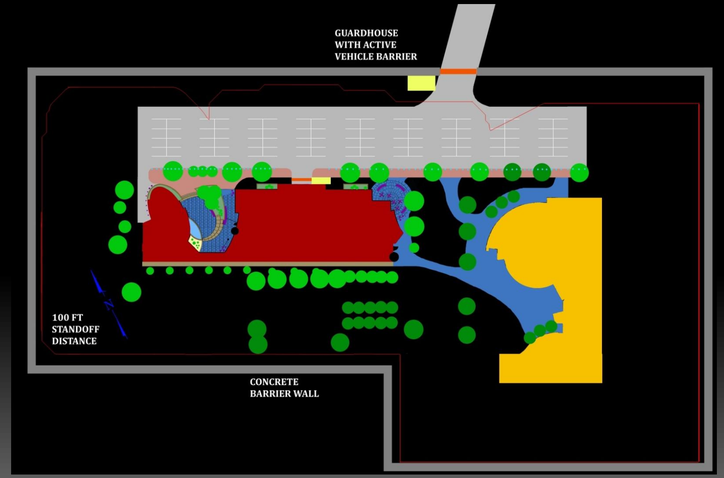
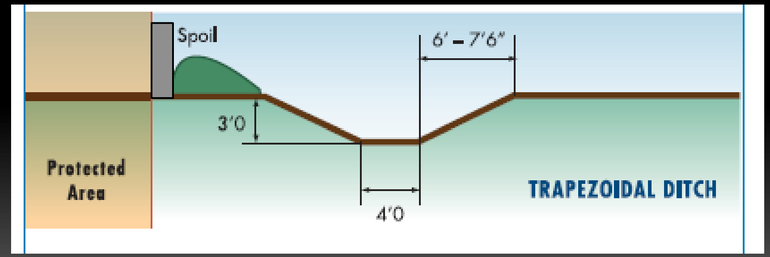
Redesigned Site Plan



Site Redesign

Alterations

100 ft. standoff distance
Location
Security Wall



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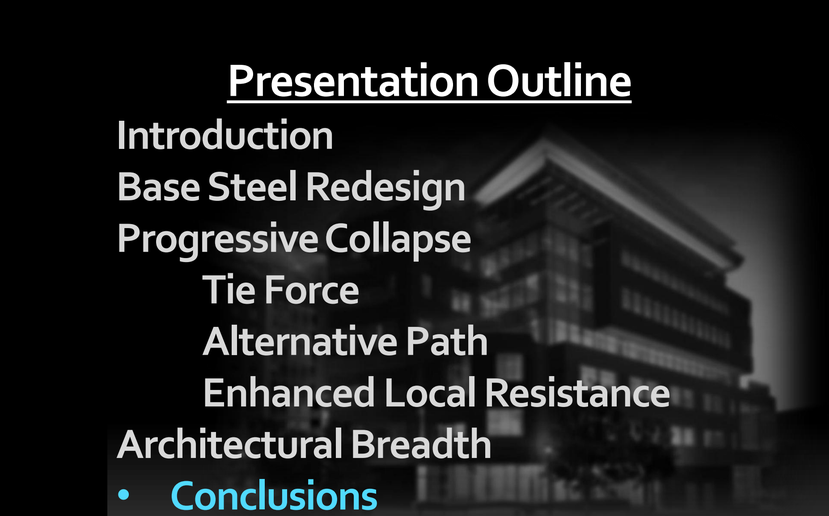


Conclusions

Goals

- ✓ Design to UFC criteria
- ✓ Explore impacts of this analysis
- ✓ Minimal architectural impact

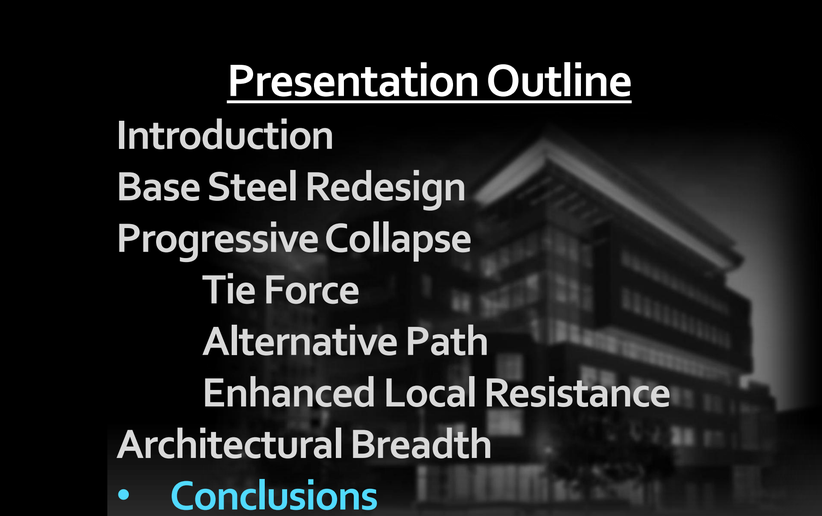
Costs

Progressive Collapse Requirements

Slab Reinforcement: 596% Increase
Columns: 113% Increase
Beams: 9.9% Increase

Total Superstructure: 7.4% Increase

Presentation Outline



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Acknowledgements

PSU AE Faculty:
Dr. Boothby, Dr. Lepage, Dr. Geshwindner
EwingCole:
Brent Elleman
Cannon Design:
Brian Alesius
RISA 3D
Friends and Family

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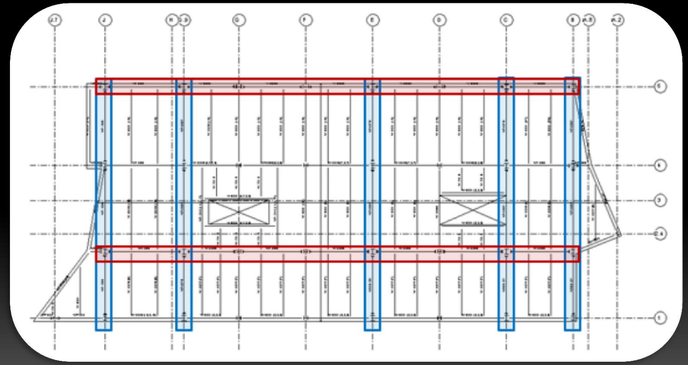
Thank You

Questions



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Introduction

Occupancies

- Mechanical Penthouse
- Executive Offices
- Offices
- Daycare
- Auditorium
- Retail
- Parking

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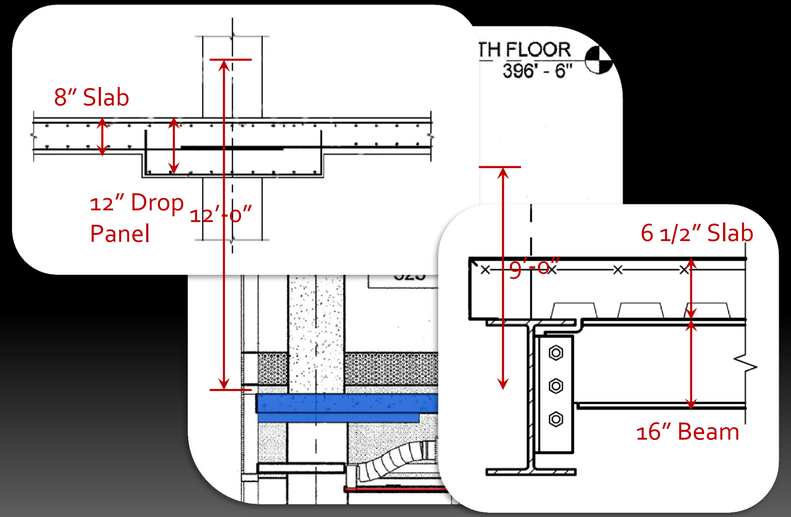
Base Steel Redesign



Layout Alterations

Floor to Floor Heights

Existing: 12'-0"
Proposed: 13'-6"
Total Building Height Increase: 10'-6"

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Progressive Collapse

UFC 3-301-01: Occupancy Categories

Occupancy Category	Nature of Occupancy	Seismic Factor I_E	Snow Factor I_S	Wind Factor I_W	Ice Factor I_I
IV	**Buildings and other structures designed as essential facilities, including, but not limited to:** • Group I-2 occupancies having surgery or emergency treatment facilities • Fire, rescue, and police stations, and emergency vehicle garages • Designated earthquake, hurricane, or other emergency shelters • Designated emergency preparedness, communication, and operation centers, and other facilities required for emergency response • Emergency backup power-generating facilities required for primary power for Category IV • Power-generating stations and other utility facilities required for primary power for Category IV, if emergency backup power generating facilities are not available • Structures containing highly toxic materials as defined by Section 307, where the quantity of material exceeds the maximum allowable quantities of Table 307.7(2) • Aviation control towers and air traffic control centers required for post earthquake operations where lack of system redundancy does not allow for immediate control of airspace and the use of alternate temporary control facilities is not feasible. Contact the authority having jurisdiction for additional guidance. • Emergency aircraft hangars that house aircraft required for post-earthquake emergency response; if no suitable back up facilities exist • Buildings and other structures not included in Category V, having DoD mission-essential command, control, primary communications, data handling, and intelligence functions that are not duplicated at geographically separate locations, as designated by the using agency • Water storage facilities and pump stations required to maintain water pressure for fire suppression	1.50	1.20	1.15	1.25

Requirements

• Buildings and other structures not included in Category V, having DoD mission-essential command, control, primary communications, data handling, and intelligence functions that are not duplicated at geographically separate locations, as designated by the using agency

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Progressive Collapse

UFC 4-023: Design Requirements

Occupancy Category	Design Requirement
I	No specific requirements
II	Option 1: Tie Forces for the entire structure and Enhanced Local Resistance for the corner and penultimate columns or walls at the first story. **OR** Option 2: Alternate Path for specified column and wall removal locations.
III	Alternate Path for specified column and wall removal locations; Enhanced Local Resistance for all perimeter first story columns or walls.
IV	Tie Forces; Alternate Path for specified column and wall removal locations; Enhanced Local Resistance for all perimeter first and second story columns or walls.

Requirements

Tie Force

Develop tensile strength in floor

Alternative Path

Span over removed column

Enhanced Local Resistance

Strengthen columns to resist blast

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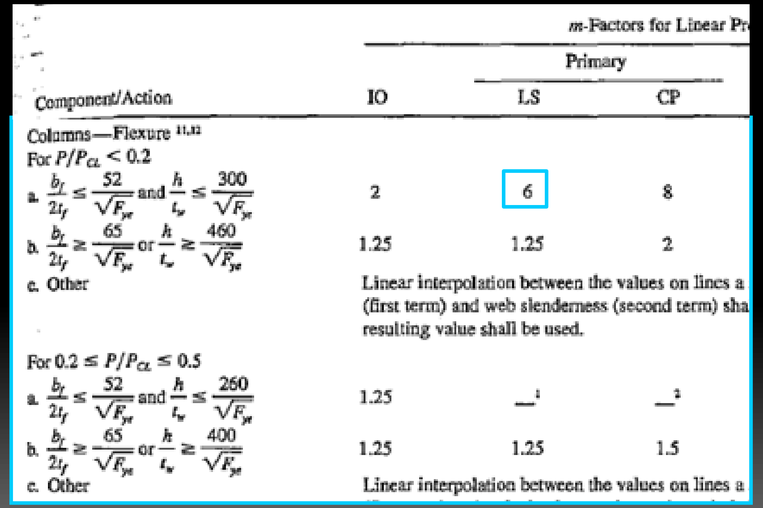
Progressive Collapse



Component/Action	m-Factors for Linear Pr		
		Primary	
	IO	LS	CP
Columns—Flexure [11,12]			
For $P/P_{CL} < 0.2$			
a. $\frac{b_f}{2t_f} \le \frac{52}{\sqrt{F_{ye}}}$ and $\frac{h}{t_w} \le \frac{300}{\sqrt{F_{ye}}}$	2	6	8
b. $\frac{b_f}{2t_f} \ge \frac{65}{\sqrt{F_{ye}}}$ or $\frac{h}{t_w} \ge \frac{460}{\sqrt{F_{ye}}}$	1.25	1.25	2
c. Other	Linear interpolation between the values on lines a (first term) and web slenderness (second term) sha resulting value shall be used.		
For $0.2 \le P/P_{CL} \le 0.5$			
a. $\frac{b_f}{2t_f} \le \frac{52}{\sqrt{F_{ye}}}$ and $\frac{h}{t_w} \le \frac{260}{\sqrt{F_{ye}}}$	1.25	—[1]	—[2]
b. $\frac{b_f}{2t_f} \ge \frac{65}{\sqrt{F_{ye}}}$ or $\frac{h}{t_w} \ge \frac{400}{\sqrt{F_{ye}}}$	1.25	1.25	1.5
c. Other	Linear interpolation between the values on lines a		

Alternative Path Analysis

Columns:

20% Axial Capacity Limit
>50% Axial Capacity is Force Controlled
Life Safety Values

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Progressive Collapse

ASCE 41: Steel m-factors

Component/Action	*m*-Factors for Linear Procedures				
		Primary		Secondary	
	IO	LS	CP	LS	CP
Beams—Flexure					
a. $\frac{b_f}{2t_f} \le \frac{52}{\sqrt{F_{ye}}}$ and $\frac{h}{t_w} \le \frac{418}{\sqrt{F_{ye}}}$	2	6	8	10	12
b. $\frac{b_f}{2t_f} \ge \frac{65}{\sqrt{F_{ye}}}$ or $\frac{h}{t_w} \ge \frac{640}{\sqrt{F_{ye}}}$	1.25	2	3	3	4
c. Other	Linear interpolatio n between the values on lines a and b for both flange slendern (first term) and web slenderness (second term) shall be performed, and the lowes resulting value shall be used.				

Alternative Path Analysis

Columns:

20% Axial Capacity Limit

>50% Axial Capacity is Force Controlled

Life Safety Values

Beams:

>20% Axial Capacity is Force Controlled

Primary: Frames & Girders

Secondary: Infill Beams

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Progressive Collapse

UFC 023: Connection m-factors

Connection Type	Linear Acceptance Criteria *m*-factors	
	Primary[1]	Secondary[1]
Fully Restrained Moment Connections		
Improved WUF with Bolted Web	2.3 – 0.021d	4.9 – 0.048d
Reduced Beam Section (RBS)	4.9 – 0.025d	6.5 – 0.025d
WUF	4.3 – 0.083d	4.3 -0.048d
SidePlate®	6.7 – 0.039d[2]	11.1 – 0.062d

Alternative Path Analysis

Connections:

Full Penetration Moment Connections

Deeper Members Result in Lower m-Factors

Typically between 2-3

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Alternative Path Analysis

Analysis Spreadsheet

REMOVAL OF COLUMN F5 at 1st Story - PRIMARY ELEMENTS										
Element Name	Next to Removed	Size	Connection Type	Connection m-factor	$P_u/\Phi P_{CL}$ (15)	$M_{uz}/\Phi M_{CLz}$	$M_{uy}/\Phi M_{CLy}$	Element m-factor (7)	Interaction ≤ 1.0	$V_u/\Phi V_{CL}$ ≤ 1.0
C,L,E5	Y	W14X500	Fixed Base	---	0.66	0.03	0.32	Col Mom Force Cont (8)	0.97	0.02
C,L,F5	Y	W14X193	Fixed Base	---	0.04	0.02	0.00	6.00	0.02	0.01
C,L,G5	Y	W14X193	Fixed Base	---	1.54	0.55	0.00	Col Mom Force Cont (8)	2.04	0.19
C,L,G.95	N	W14X500	Fixed Base	---	0.25	0.01	0.03	5.58	0.26	0.00
C,L,J5	N	W14X211	Fixed Base	---	0.24	0.06	0.12	5.73	0.27	0.01
C,U,C5	N	W14X500	Fixed Base	---	0.29	0.03	0.05	5.14	0.30	0.01
C,U,D5	N	W14X120	Fixed Base	---	1.49	0.03	0.00	Col Mom Force Cont (8)	1.52	0.01
C,U,E5	Y	W14X500	Fixed Base	---	0.72	0.03	0.40	Col Mom Force Cont (8)	1.11	0.02
C,U,F5	Y	W14X120	Fixed Base	---	0.92	0.09	0.00	Col Mom Force Cont (8)	1.00	0.02
C,U,G5	Y	W14X120	Fixed Base	---	3.11	0.99	0.00	Col Mom Force Cont (8)	3.99	0.22

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Progressive Collapse

Results

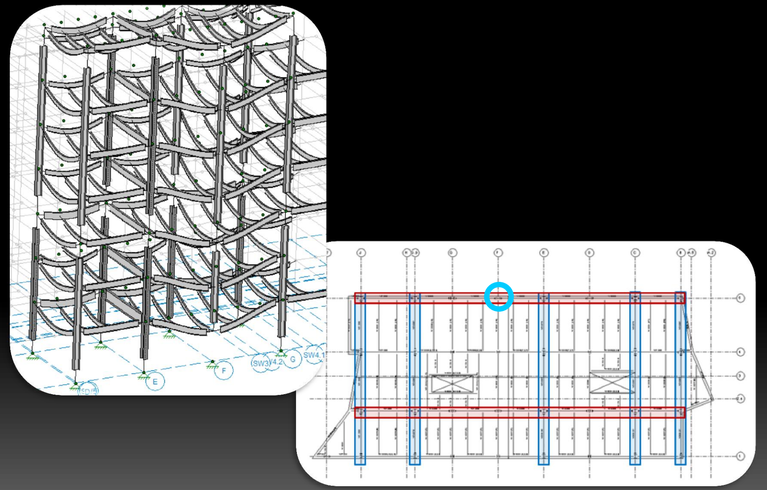
Existing Column Results

Location	Size	Pu/ΦPn	Mu/ΦMn	m-factor	Interaction
Exterior Moment Frame	W14x193	1.54	0.55	Force Controlled: 1.0	2.03
Interior Gravity Column	W14x120	2.10	0.00	Force Controlled: 1.0	2.10

Table 7.2: Frame Sizes That Pass Removal of Column F5 Scenario

	Typical Lower Column	Typical Upper Column	Typical 2nd Floor Beam	Typical 3rd Floor Beam	Typical 4th+ Floor Beam
North-South Frames (C, E, & G.9)	W14x370	W14x370	W36x182	W30x108	W24x76
North-South Frames (B & J)	W14x370	W14x370	W36x182	W30x108	W24x76
East West Frames (1&5)	W14x370	W14x370	W21x68	W21x68	W21x68
East West Frames (2)	W14x370	W14x370	W18x50	W18x50	W18x50
Gravity Columns	W14x132	W14x82	---	---	---

Alternative Path Analysis



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Architecture Breadth

UFC 010 Minimum Standoff Distances

18 ft.

Distance to:	Building Category	Standoff Distances: Applicable Level of Protection	Conventional Construction Standoff Distance: Load Bearing Walls [1]	Conventional Construction Standoff Distance: Non-Load Bearing Walls [1]	Minimum Standoff Distance [2]	Applicable Explosive Weight [3]
Controlled Perimeter or Parking and Roadways without a Controlled Perimeter	Billeting and High Occupancy Family Housing	Low	A	C	18 ft (5.5 m)	I
	Primary Gathering Building	Low	A	C	18 ft (5.5 m)	I
	Inhabited Building	Very Low	B	D	18 ft (5.5 m)	I

Site Redesign

UFC 010 Conventional Construction Standoff Distances

151 ft.

Wall Type	Column Letter A	B	C	D	E	F	G	H
Wood Studs – Brick Veneer	105 ft (32 m)	105 ft (32 m)	79 ft (24 m)	66 ft (20 m)	36 ft (11 m)	36 ft (11 m)	23 ft (7 m)	16 ft (5 m)
Wood Studs – EIFS	207 ft (63 m)	207 ft (63 m)	164 ft (50 m)	141 ft (43 m)	85 ft (26 m)	85 ft (26 m)	66 ft (20 m)	56 ft (17 m)
Metal Studs – Brick Veneer	187 ft (57 m)	108 ft (33 m)	207 ft [4] (63 m)	186 ft [4] (57 m)	75 ft (23 m)	43 ft (13 m)	82 ft [4] (25 m)	75 ft [4] (23 m)
Metal Studs – EIFS	361 ft (110 m)	207 ft (63 m)	420 ft [4] (128 m)	361 ft [4] (110 m)	151 ft (46 m)	85 ft (26 m)	167 ft [4] (51 m)	151 ft [4] (46 m)
Metal Panels	n/a [1]	n/a [1]	151 ft (46 m)	108 ft (33 m)	n/a [1]	n/a [1]	56 ft (17 m)	39 ft (12 m)

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Construction Management Breadth

Base Design Cost and Schedule

Floor	System	Material Take-Offs				RS Means Cost Data					Total Estimate	
		Member	Count	Unit	Total	# Studs	Crew	Daily Output	Cost (Incl O&P)	Studs Daily Output	Stud Cost (Incl O&P)	Total Cost	Total Schedule (Days)
Fifth	Beams	W12x19	12	L.F.	120.25	0	E-2	880	35.75	910	2.82	$4,299	0.14
		W14x22	20	L.F.	447.5	157	E-2	990	41.5	910	2.82	$19,014	0.62
		W16x26	2	L.F.	40.2	0	E-2	1000	46	910	2.82	$1,849	0.04
		W16X31	17	L.F.	414	230	E-2	900	54	910	2.82	$23,174	0.78
		W16x40	5	L.F.	141.85	45	E-2	800	68.5	910	2.82	$3,844	0.23
		W18x35	5	L.F.	126.75	63	E-2	960	62	910	2.82	$8,036	0.20
		W18x40	2	L.F.	44	34	W-2	360	63.5	910	2.82	$3,154	0.08
		W18x50	10	L.F.	221.85	0	E-2	912	85	910	2.82	$18,857	0.24
		W21x44	2	L.F.	56.75	56	E-2	1064	68	910	2.82	$4,017	0.11
		W21x55	4	L.F.	107.1	0	E-2	1064	92.75	910	2.82	$9,934	0.10
		W24x62	8	L.F.	194.3	0	E-2	1110	92	910	2.82	$17,876	0.18
		W24x76	2	L.F.	22	8	E-2	1110	111	910	2.82	$2,465	0.03
		W27x84	3	L.F.	26	0	E-2	1190	121	910	2.82	$3,146	0.02
		Total A992 Steel	32		1962.6	653						**$125,663**	**2.8**
	Connections	Moment Connections	44	Ea.			E-14	9.6	115			$5,060	4.6
		Cantilever Connections	4	Ea.			E-14	9.6	115			$460	0.4
		Total Rigid Connections										**$5,520**	**5.0**
	Deck	22 Ga 2"VLI		S.F.	9637.7		E-4	3560	2.24			$21,588	2.71
		6x6- W2.1xW2.1		C.S.F.	9.6377		2 Rodm	31	61			$588	0.31
		4500 psi Concrete		C.Y.	133.3		C-20		116			$22,423	
		Pump Placing, Elev. Slab		C.Y.	133.3		C-20	140	28			$5,412	1.38
		Total Floor System										**$50,012**	**4.4**

Cost

Deck Reinf: $12,500
Columns: $829,900
Beams: $948,300
Connections: $39,100

Total: $2.15 million
$17.52 / SF

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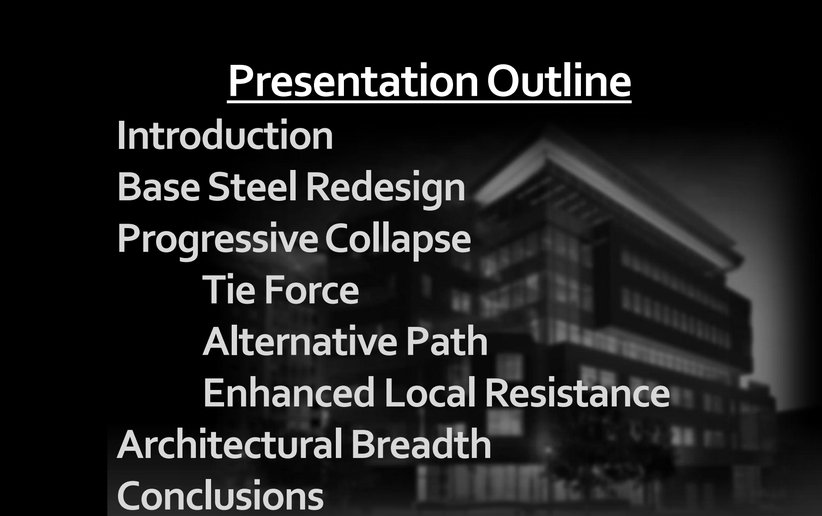

Construction Management Breadth

Base Steel: $17.52 / SF
Progressive Collapse: $18.8 / SF
Existing Concrete: $16.39 / SF

Cost

Deck Reinf: $87,021
Columns: $1.77 million
Beams: $1.04 million
Connections: $58,600

Total: $2.31 million
$18.80 / SF

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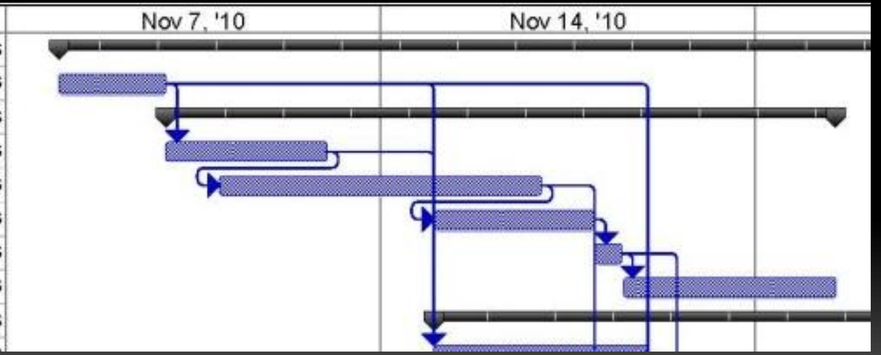
Construction Management Breadth

Base Steel Schedule

ID	Task Name	Duration
1	**Office Tower Structure**	**33 days**
2	Base Column Erection	2 days
3	**Second Floor**	**8.5 days**
4	Steel Erection	3 days
5	Rigid Connections	4 days
6	Place Deck	3 days
7	Place Reinforcing	0.5 days
8	Pour Concrete	2 days
9	**Third Floor**	**10 days**



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Construction Management Breadth

Pro Collapse Schedule

ID	Task Name	Duration
1	**Office Tower Structure**	**44.5 days**
2	Base Column Erection	2 days
3	**Second Floor**	**11 days**
4	Steel Erection	3 days
5	Rigid Connections	4.5 days
6	Place Deck	3 days
7	Place Reinforcing	2.5 days
8	Pour Concrete	2 days
9	**Third Floor**	**13 days**