STRUCTURAL DESIGN & PROGRESSIVE COLLAPSE

"the most comprehensive cancer care facility between Boston and New York City, offering patients state-of-the-art care and treatment."

PRESENTATION OUTLINE:

- Smilow Cancer Hospital Overview
- Depth Study
  - Structural System Redesign
  - Progressive Collapse Design
- Breadth Study
  - Blast-Resistant Glazing
- Conclusions

PROJECT OVERVIEW

BUILDING STATISTICS:

- *Owner:* Yale-New Haven Hospital
- 497,000 square feet
- 14 patient floors + 2 mechanical floors
- *Dates of Construction:* September 2006 – October 2009
- *Overall Project Cost:* $253 M
- *Delivery Method:* Design-Bid-Build with GMP

PROJECT TEAM:

- *Owner* - Yale-New Haven Hospital
- *Architect* - Shepley Bulfinch Richardson & Abbott
- *Construction Manager* - Turner Construction Company
- *Structural Engineer* – Spiegel Zamecnik & Shah
- *Mech./Elec./Plumbing* – BR+A Consulting Engineers

CURRENT DESIGN:

- Architectural
  - Part of the Yale-New Haven Hospital Complex
  - Unitized curtain wall panel system: glass + terra cotta
  - Two-story lobby with three-story glass awning overhanging front of building
  - Roof system: combination cast-in-place concrete and metal roof decking

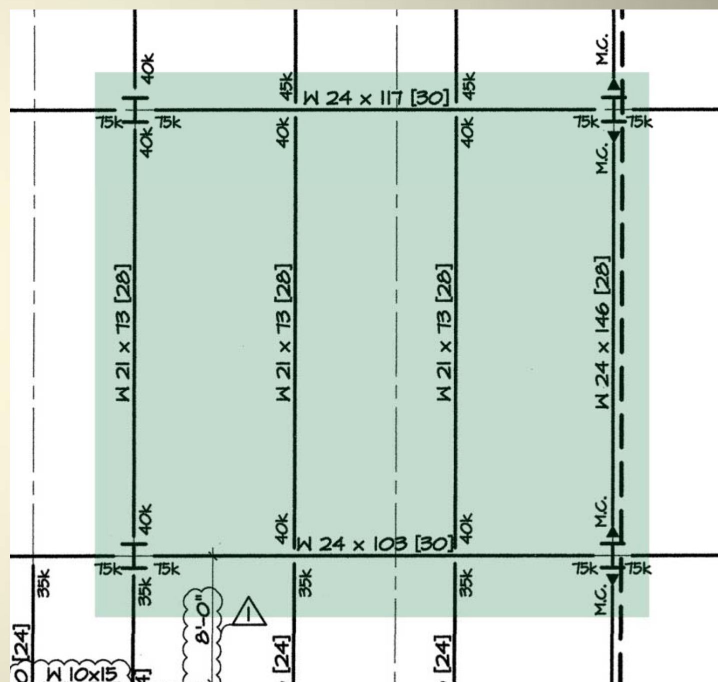
CURRENT DESIGN:

- M.E.P.
  - 8 air-handling units: 6 on 5th floor + 2 on roof; 70,000 cfm per AHU
  - 480/277V + 208/120V 3 phase, 4 wire systems
  - Emergency power: (3) 2000kW/ 2500kVA diesel generators

STRUCTURAL DEPTH

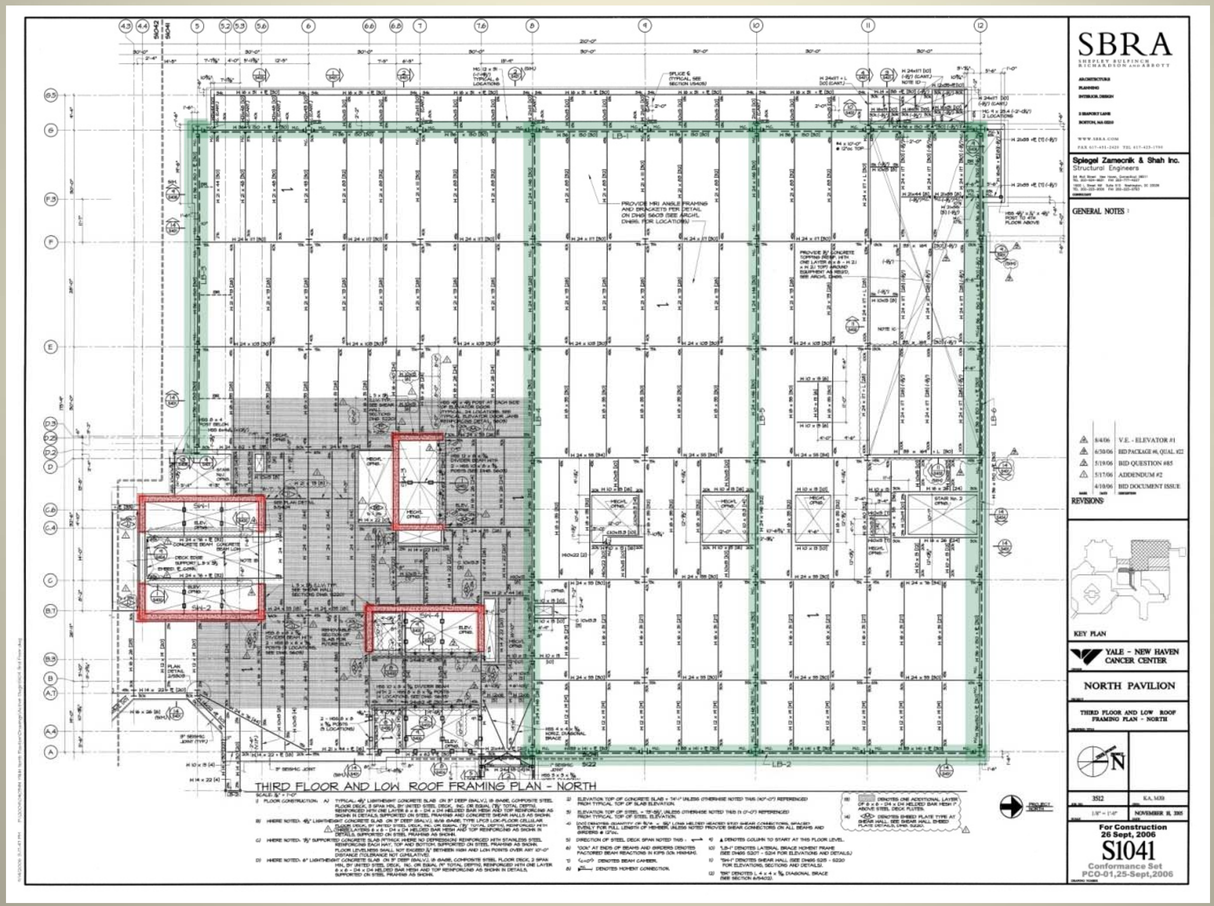
STRUCTURAL DEPTH:

- Current Structural System
  - Steel Moment & Gravity Frames + (4) Reinforced Concrete Shear Walls
  - Typical Bay: 30’ x 30’
  - Floor System: 4-1/2” thick concrete slab on 3” metal deck
  - Beams: W18/21/24
  - Girders: W24
  - Columns: W12/14/24, HSS, cruciform, reinforced concrete
  - Foundation: 4’ thick reinforced concrete mat slab (8’ at shear wall locations)



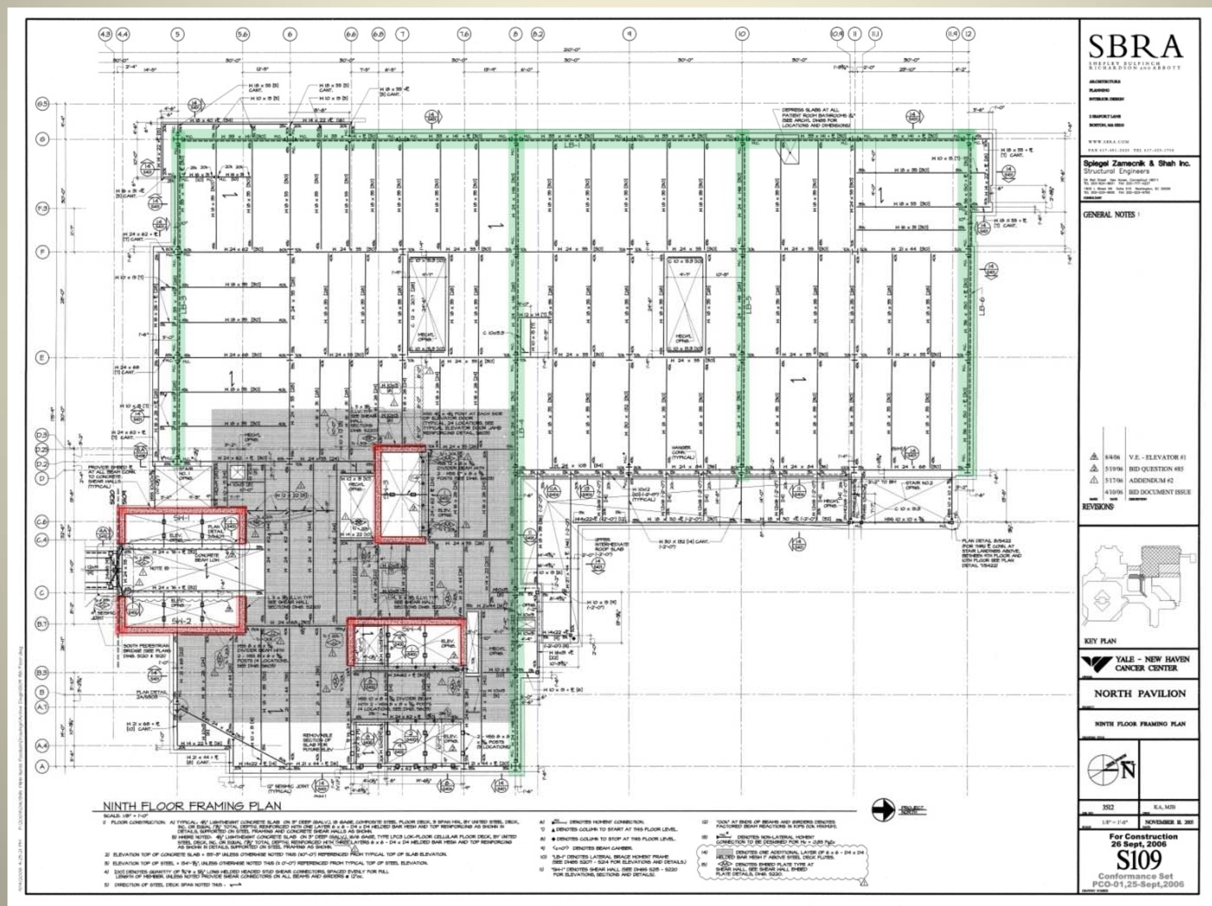
STRUCTURAL DEPTH:

- Typical Framing Plan: Floors 1 - 5



STRUCTURAL DEPTH:

- Typical Framing Plan: Floors 7 - 17



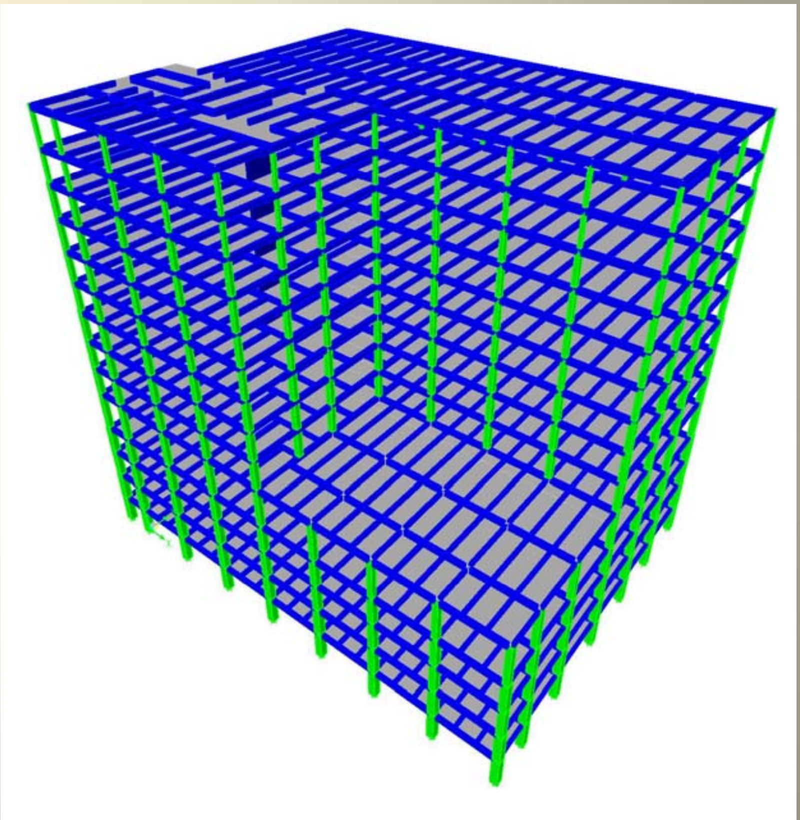
STRUCTURAL DEPTH:

- Proposed Reinforced Concrete Structural System
  - Design criteria based on ACI 318-05
  - ASCE 7 Load Combination: *1.2D + 1.0E + 1.0L + 0.2S*
  - *Typical* flexural members designed for moment and shear capacities as well as live load deflection.
  - *Typical* interior columns designed for axial loads using design aid charts from *Design of Concrete Structures*, 13th edition, by Nilson, Darwin, and Dolan.

(K_n versus R_n charts)

STRUCTURAL DEPTH:

- Proposed Reinforced Concrete Structural System
  - Concrete Moment Frames + Existing Shear Walls
  - Typical Bay: 30' x 30' (with intermediate beams at 10')
  - Floor Slab: 5" thick, one-way floor slab (ACI deflection criteria)
  - Beams: 12" x 25"
  - Girders: 16" x 30"
  - Interior Columns: 16" x 16" to 40" x 40"



STRUCTURAL DEPTH:

- Progressive Collapse Design

“…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.”

ASCE 7-02

Progressive collapse design in the U.S. governed by Unified Facilities Criteria (UFC) 4-023-03 “Design of Buildings to Resist Progressive Collapse” published by the Dept. of Defense.

Ronan Point Apartment Tower Collapse
London, 1968
wikipedia.org

STRUCTURAL DEPTH:

- Progressive Collapse Design
  - UFC 4-023-03 outlines two design approaches: direct and indirect.
  - Direct method relies on the idea of an "alternate path" and typically means beams and girders must be designed for longer spans as columns are "removed" from the structure.
  - Indirect method relies on the "catenary" response of the structure. Goal is to develop adequate tie forces within beams and slabs. Allows for evacuation time in the event of column failure.

STRUCTURAL DEPTH:

- Progressive Collapse Design

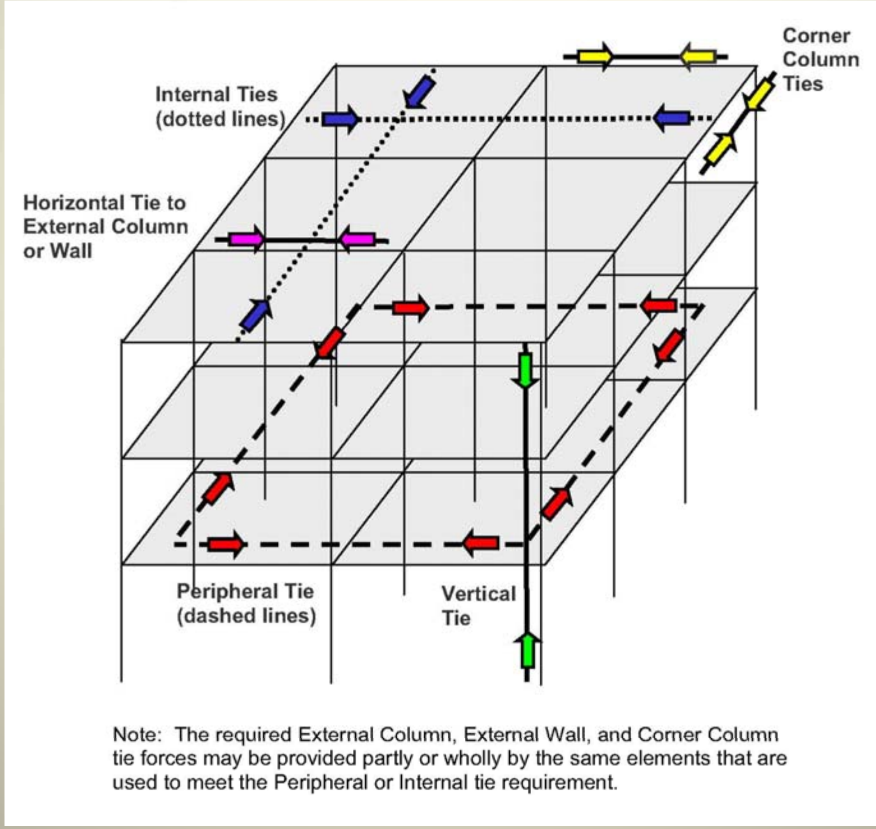
  • Smilow Cancer Hospital assigned a Low Level of Protection (LLOP); therefore, only Indirect Method required.

  • Blast Scenarios:

  1. Corner Column Failure
  2. Interior Column Failure

STRUCTURAL DEPTH:

- Progressive Collapse Design
  - Location of required ties for Indirect Method:



STRUCTURAL DEPTH:

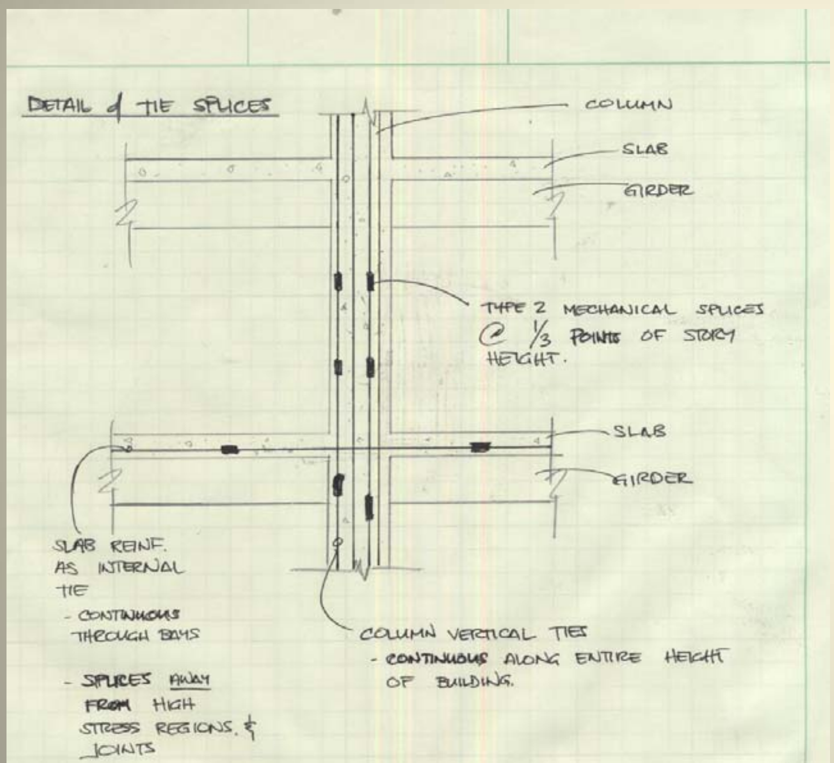
- Progressive Collapse Design

Tie Location	Tie Force (kips)	Required Steel Area (in^2)	Provided Steel Area (in^2)
Peripheral	13.5	0.24	0.31
Internal (N-S)	6.45 per foot width	0.12 per foot width	0.27 per foot width
Internal (E-W)	6.45 per foot width	0.12 per foot width	0.62 per foot width
Horizontal (N-S)	24.7	0.44	4.00
Horizontal (E-W)	24.7	0.44	6.35
Vertical	121.5	2.16	10.16
Corner Column	24.7	0.44	6.35

Provided flexural reinforcement in slabs, beams, girders, and columns are adequate to develop required tie forces. Reinforcement must now be detailed to meet the ductility requirements for the indirect method.

STRUCTURAL DEPTH:

➢ Progressive Collapse Design



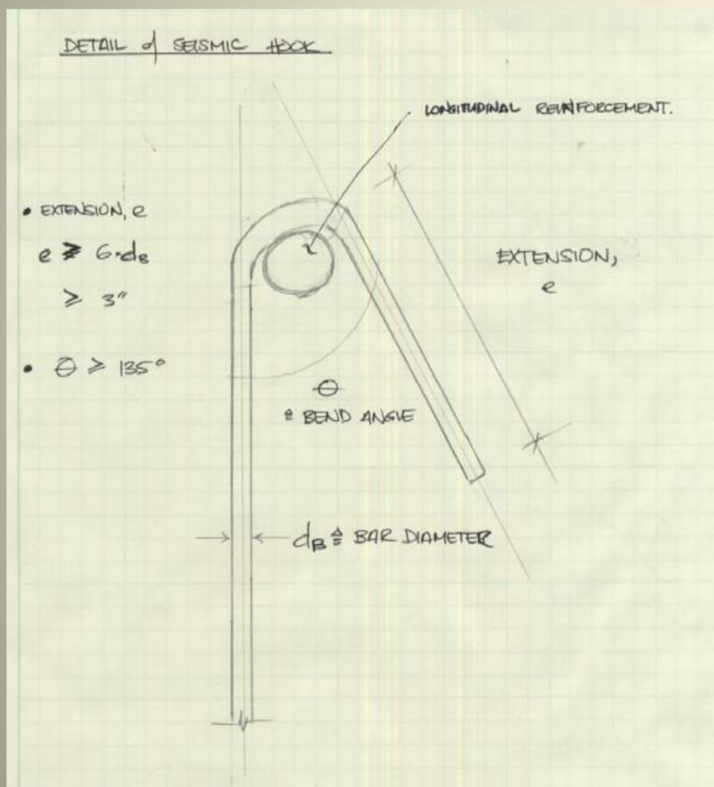
Detailing Requirements:

• Vertical ties to be continuous along *entire* height of building with Type 2 mechanical splices at *third* points of column heights.

• Horizontal ties to be continuous through bays with splices *away* from joints and regions of high stress.

STRUCTURAL DEPTH:

- Progressive Collapse Design



Detailing Requirements:

- "Seismic" hook to be used at all tie interfaces.

BREADTH STUDY

BLAST-RESISTANT GLAZING:

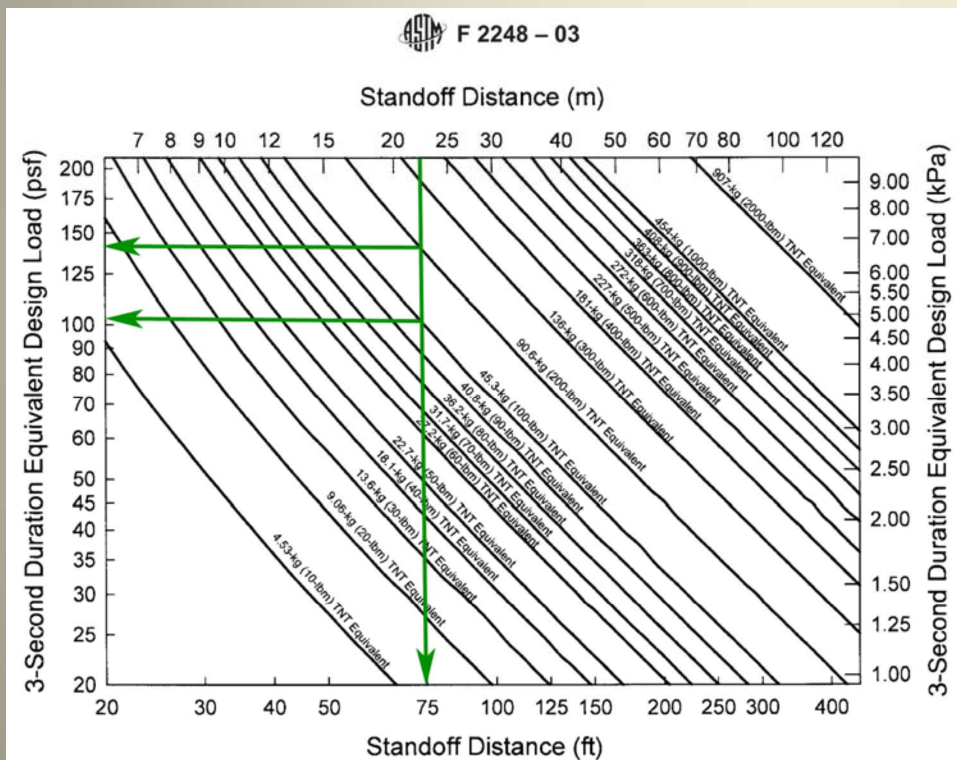
➢ Design Criteria

- Design blast pressures are based on charge size and stand-off distance.
- Primary design goal is to mitigate the effects of flying glass shards due to blast pressures.
- Glass fracture is not only acceptable, but expected.
- Blast design based on ASTM F 2248 standard.

Oran Safety Glass® (OSG)

BLAST-RESISTANT GLAZING:

- Design Criteria



ASTM F 2248: Specifying an Equivalent 3-second Duration Design Loading for Blast Resistant Glazing

- ASTM F 2248 chart relates stand-off distance and charge mass to 3-second equivalent design load.

Stand-off distance = 75’

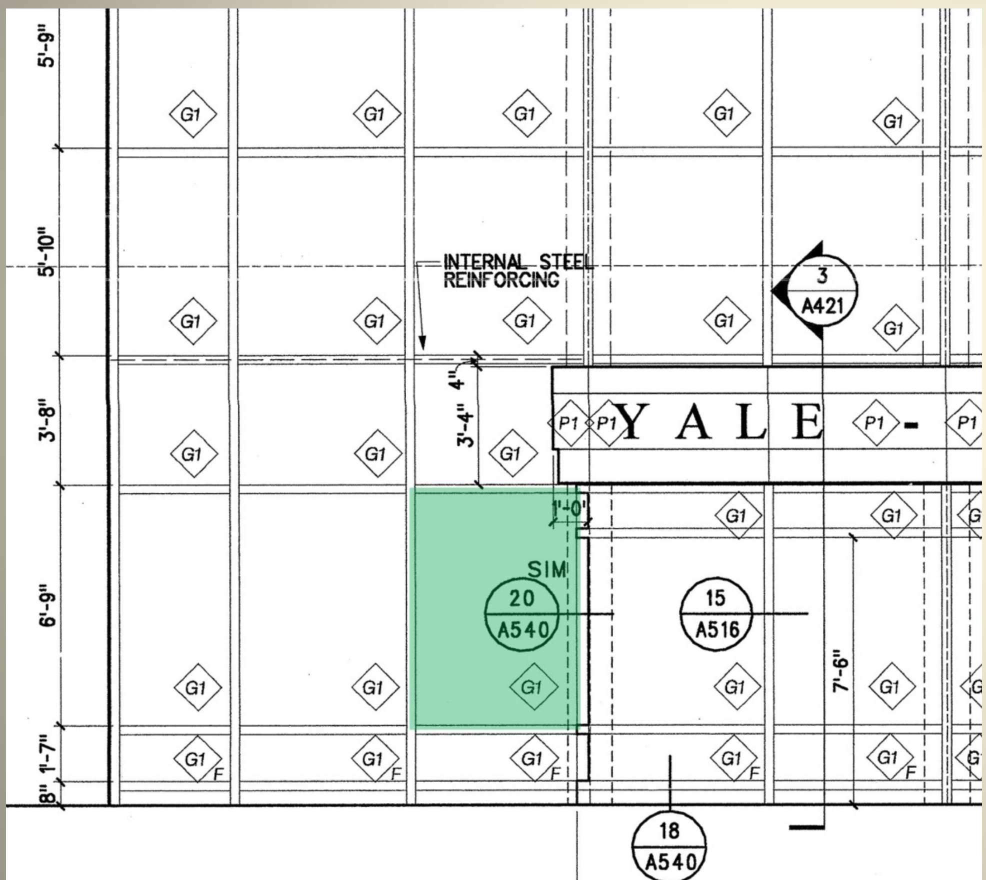
Charge Mass = 100 lbm & 200 lbm

- **3-second Design Load = 100 psf & 140 psf**

* Typical Design Wind Load = 15-20 psf

BLAST-RESISTANT GLAZING:

- Existing Design Analysis



- Critical glazing panel on first floor lobby façade:

  6'-9" x 5'-0" (81" x 60")

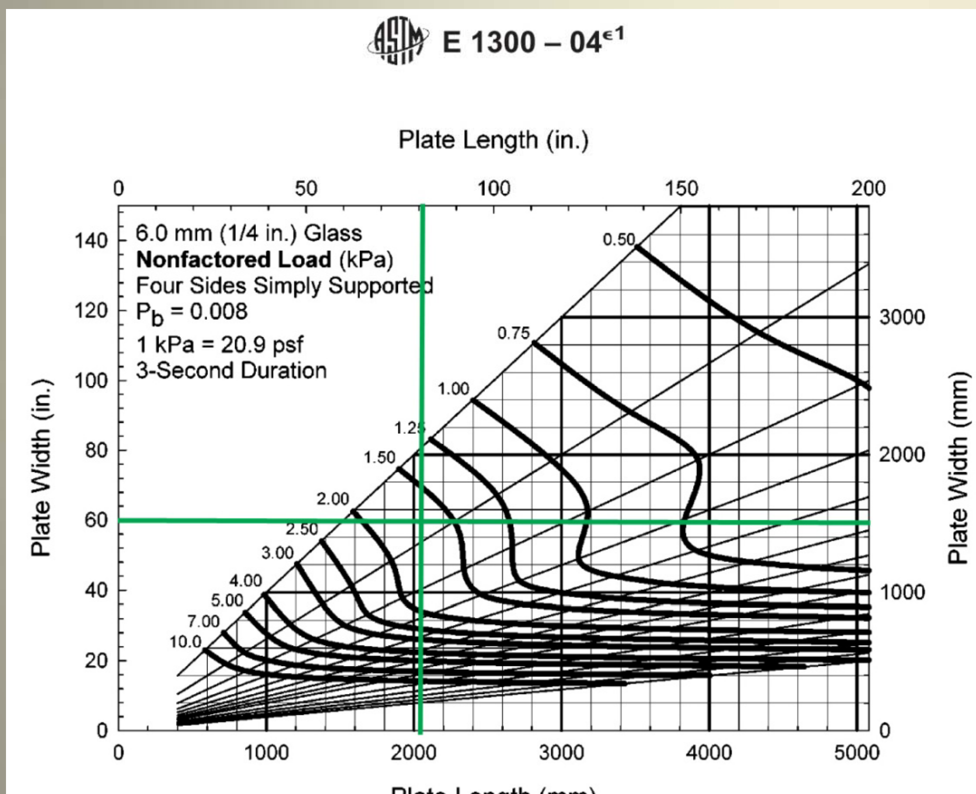
  A = 33.75 sq. ft. (4860 sq. in.)

  Aspect Ratio = 1.35

  1" Insulating Glass Unit (IGU)
  - (2) ¼" HS lites
  - ½" air space

BLAST-RESISTANT GLAZING:

➢ Existing Design Analysis



ASTM E 1300: Determining Load Resistance of Glass in Buildings

- ASTM E 1300 charts give base load-resistance value for annealed glass (non-factored load or NFL).

- For critical panel,

  NFL = 1.70 kPa or 35.5 psf

BLAST-RESISTANT GLAZING:

- Existing Design Analysis

TABLE 2 Glass Type Factors (GTF) for Insulating Glass (IG), Short Duration Load

Lite No. 1 Monolithic Glass or Laminated Glass Type	Lite No. 2 Monolithic Glass or Laminated Glass Type					
	AN		HS		FT	
	GTF1	GTF2	GTF1	GTF2	GTF1	GTF2
AN	0.9	0.9	1.0	1.9	1.0	3.8
HS	1.9	1.0	1.8	1.8	1.9	3.8
FT	3.8	1.0	3.8	1.9	3.6	3.6

TABLE 5 Load Share (LS) Factors for Insulating Glass (IG) U

NOTE 1—Lite No. 1 Monolithic glass, Lite No. 2 Monolithic glass, short or long duration load, or Lite N glass, short duration load only, or Lite No. 1 Laminated Glass, Lite No. 2 Laminated Glass, short or long

Lite No. 1 Monolithic Glass		Lite No. 2 Monolithic Glass, Short or Long Duration Load or Laminated Glass, S														
Nominal Thickness		2.5 (3/32)		2.7 (lami)		3 (1/8)		4 (5/32)		5 (3/16)		6 (1/4)		8 (5/16)		
mm	(in.)	LS1	LS2	LS1	LS2	LS1	LS2	LS1	LS2	LS1	LS2	LS1	LS2	LS1	LS2	LS
2.5	(3/32)	2.00	2.00	2.73	1.58	3.48	1.40	6.39	1.19	10.5	1.11	18.1	1.06	41.5	1.02	73.
2.7	(lami)	1.58	2.73	2.00	2.00	2.43	1.70	4.12	1.32	6.50	1.18	10.9	1.10	24.5	1.04	43.
3	(1/8)	1.40	3.48	1.70	2.43	2.00	2.00	3.18	1.46	4.83	1.26	7.91	1.14	17.4	1.06	30.
4	(5/32)	1.19	6.39	1.32	4.12	1.46	3.18	2.00	2.00	2.76	1.57	4.18	1.31	8.53	1.13	14.
5	(3/16)	1.11	10.5	1.18	6.50	1.26	4.83	1.57	2.76	2.00	2.00	2.80	1.56	5.27	1.23	8.6
6	(1/4)	1.06	18.1	1.10	10.9	1.14	7.91	1.31	4.18	1.56	2.80	2.00	2.00	3.37	1.42	5.2
8	(5/16)	1.02	41.5	1.04	24.5	1.06	17.4	1.13	8.53	1.23	5.27	1.42	3.37	2.00	2.00	2.8
10	(3/8)	1.01	73.8	1.02	43.2	1.03	30.4	1.07	14.5	1.13	8.67	1.23	5.26	1.56	2.80	2.0
12	(1/2)	1.01	169.	1.01	98.2	1.01	68.8	1.03	32.2	1.06	18.7	1.10	10.8	1.24	5.14	1.4
16	(5/8)	1.00	344.	1.01	199.	1.01	140.	1.02	64.7	1.03	37.1	1.05	21.1	1.12	9.46	1.2
19	(3/4)	1.00	606.	1.00	351.	1.00	245.	1.01	113.	1.02	64.7	1.03	36.4	1.07	15.9	1.1

Tables 2 & 5 from ASTM E 1300 Standard

- ASTM E 1300 tables give modification factors for different glass types/configurations.
- For heat-strenghtened glass, GTF = 1.8 [Table 2]
- For IGUs with both lites @ ¼”, LSF = 2.0 [Table 5]

- Load Resistance = NFL x GTF x LSF

= 35.5 psf x 1.8 x 2.0

= 128 psf

Therefore, current design is good for 100 lb charge, but not for 200 lb charge.

BLAST-RESISTANT GLAZING:

➢ Design for Blast-Resistance

TABLE 2 Glass Type Factors (GTF) for Insulating Glass (IG), Short Duration Load

Lite No. 1 Monolithic Glass or Laminated Glass Type	Lite No. 2 Monolithic Glass or Laminated Glass Type					
	AN		HS		FT	
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AN	0.9	0.9	1.0	1.9	1.0	3.8
HS	1.9	1.0	1.8	1.8	1.9	3.8
FT	3.8	1.0	3.8	1.9	3.6	3.6

TABLE 5 Load Share (LS) Factors for Insulating Glass (IG) U

NOTE 1—Lite No. 1 Monolithic glass, Lite No. 2 Monolithic glass, short or long duration load, or Lite N glass, short duration load only, or Lite No. 1 Laminated Glass, Lite No. 2 Laminated Glass, short or long

Lite No. 1 Monolithic Glass		Lite No. 2 Monolithic Glass, Short or Long Duration Load or Laminated Glass, S														
Nominal Thickness		2.5 (3⁄32)		2.7 (lami)		3 (1⁄8)		4 (5⁄32)		5 (3⁄16)		6 (1⁄4)		8 (5⁄16)		
mm	(in.)	LS1	LS2	LS1	LS2	LS1	LS2	LS1	LS2	LS1	LS2	LS1	LS2	LS1	LS2	LS
2.5	(3⁄32)	2.00	2.00	2.73	1.58	3.48	1.40	6.39	1.19	10.5	1.11	18.1	1.06	41.5	1.02	73.
2.7	(lami)	1.58	2.73	2.00	2.00	2.43	1.70	4.12	1.32	6.50	1.18	10.9	1.10	24.5	1.04	43.
3	(1⁄8)	1.40	3.48	1.70	2.43	2.00	2.00	3.18	1.46	4.83	1.26	7.91	1.14	17.4	1.06	30.
4	(5⁄32)	1.19	6.39	1.32	4.12	1.46	3.18	2.00	2.00	2.76	1.57	4.18	1.31	8.53	1.13	14.
5	(3⁄16)	1.11	10.5	1.18	6.50	1.26	4.83	1.57	2.76	2.00	2.00	2.80	1.56	5.27	1.23	8.6
6	(1⁄4)	1.06	18.1	1.10	10.9	1.14	7.91	1.31	4.18	1.56	2.80	2.00	2.00	3.37	1.42	5.2
8	(5⁄16)	1.02	41.5	1.04	24.5	1.06	17.4	1.13	8.53	1.23	5.27	1.42	3.37	2.00	2.00	2.8
10	(3⁄8)	1.01	73.8	1.02	43.2	1.03	30.4	1.07	14.5	1.13	8.67	1.23	5.26	1.56	2.80	2.0
12	(1⁄2)	1.01	169.	1.01	98.2	1.01	68.8	1.03	32.2	1.06	18.7	1.10	10.8	1.24	5.14	1.4
16	(5⁄8)	1.00	344.	1.01	199.	1.01	140.	1.02	64.7	1.03	37.1	1.05	21.1	1.12	9.46	1.2
19	(3⁄4)	1.00	606.	1.00	351.	1.00	245.	1.01	113.	1.02	64.7	1.03	36.4	1.07	15.9	1.1

Tables 2 & 5 from ASTM E 1300 Standard

• To design for a 200 lb charge (140 psf), change glass type to fully-tempered (FT).

• For *fully-tempered* glass, ***GTF = 3.6*** [Table 2]

• For IGUs with both lites @ ¼", LSF = 2.0 [Table 5]

➢ Load Resistance = NFL x GTF x LSF

= 35.5 psf x ***3.6*** x 2.0

= *256 psf* > 140 psf

Use fully-tempered, laminated glass for blast-resistant design.

BLAST-RESISTANT GLAZING:

➢ Heat-Strengthened versus Fully-Tempered Glazing

Heat-Strengthened

- Low level of residual stress
- Some waviness from heat treatment
- Tends to stay in opening after fracture, but can break into large, sharp pieces under blast loads

Fully-Tempered

- High level of residual stress
- Visible waviness from heat treatment
- Breaks into relatively harmless "diced" pattern
- About twice as strong as HS, but at a cost premium

CONCLUSIONS

CONCLUSIONS:

- Progressive Collapse
  - Designing for progressive collapse using the Indirect Method is a feasible option.
  - For concrete structures, existing reinforcement is usually adequate to develop required tie forces.
  - Proper detailing of tie splices and connections is CRITICAL.
- Blast-Resistant Glazing
  - Increasing stand-off distance is the best way to mitigate glazing failure due to blast loads.
  - Fully-tempered, laminated glass is the preferred material for blast-resistant glazing design.
  - The probability of an explosive attack must be assessed as accurately as possible, and the need for blast-resistant glazing must be determined accordingly.

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QUESTIONS & COMMENTS