Case Study:

Guggenheim Modern Art Museum, NY

ARCH 631: Structural Systems
Prof. Anne Nichols
2011

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Overview

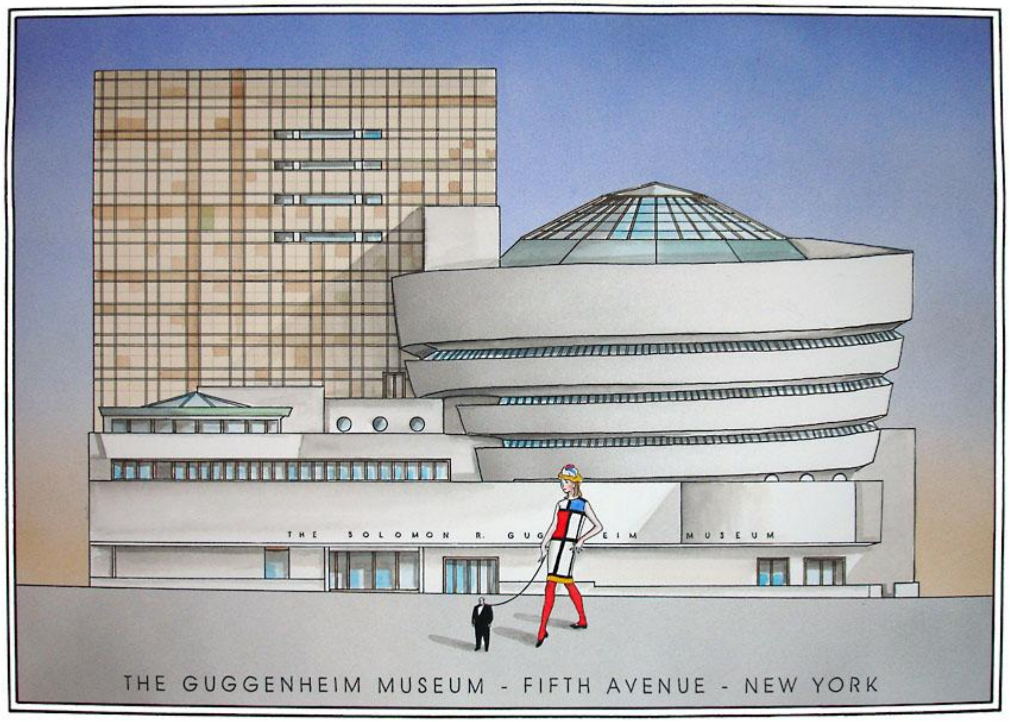
- **Solomon R. Guggenheim Museum of Modern Art**, New York City, NY. 1959

- 16 year project designed by American architect **Frank Lloyd Wright**
- 700 sketches and 6 sets of working drawing

- 51,000 ft^2 gallery space
- 15,000 ft^2 office, theater, and retail space

- 92ft tall atrium topped with expansive glass dome
- main ramp coils upward 6 floors, more than ¼ mile

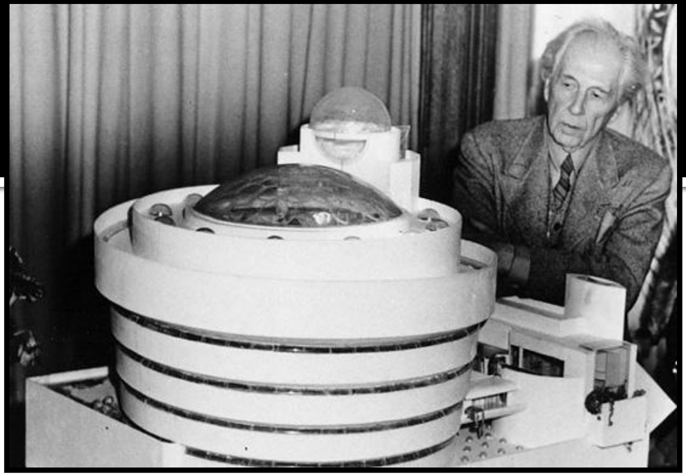
- Presentation covers….
  - building's background and history
  - layout, form, and materials
  - structural design



The Guggenheim Modern Art Museum, NY (Background)

- Founded in 1937 as Museum of
  Non-Objective Painting
- 1959 - moved to current location
  (corner of 89th St. and 5th Ave.
  opposite Central Park)
- Frank Lloyd Wright chosen as architect
- Dedicated to modern art
- Design and construction took 16 years, 1943-59, due to changes in design and costs
- Debate between architect, client, art world and public opinion, because of the contrast of its forms within the grid New York City
- Artists protested saying the sloping walls and ramp were not suitable for a painting exhibition
- October 21 - museum opened to public
- Unpopular in some criticisms made by artists who feel the building overshadows the works exhibited and that it is difficult to properly hang the paintings

The Architect (Background)

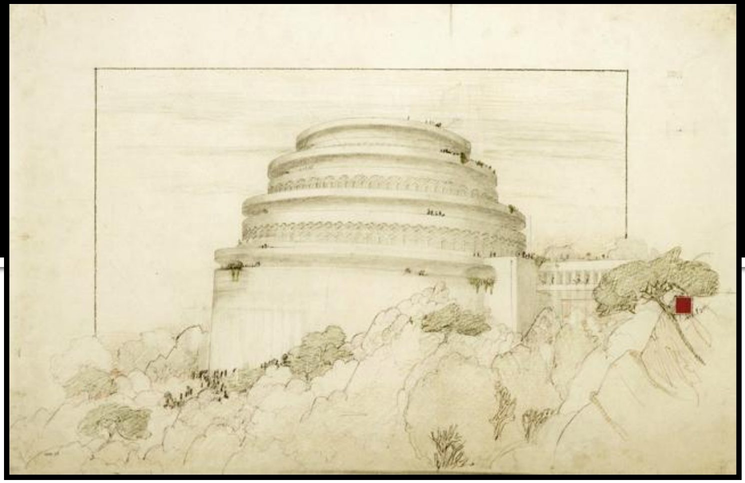


- **Frank Lloyd Wright**
- Born June 8, 1867
- American architect, interior designer, writer and educator
- Designed more than 1,000 structures and completed 500 works
- Believed in designing structures that were in harmony with humanity and its environment – “organic architecture”
- Works include houses, offices, churches, schools, skyscrapers, hotels, and museums
- Also designed interior elements of his buildings, such as the furniture and stained glass
- 1991 - Recognized by the AIA as "the greatest American architect of all time"

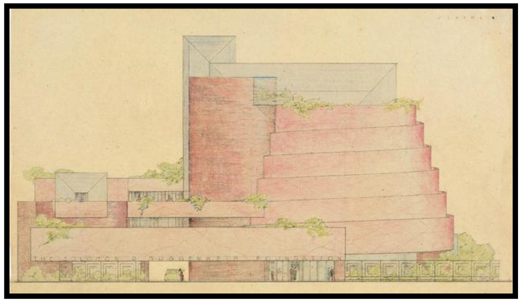
The Museum (Body)

Design Concept

- Building inspired by Wright's love for the automobile – Planetarium – designed for visitors to drive up the ziggurat-like ramps.
- In the Guggenheim, Wright intended to allow visitors to experience the collection paintings by taking an elevator to the top level then view artworks by descending the central spiral ramp
- Museum currently designs exhibits to be viewed walking up the ramp rather than walking down
- From street, building looks like a white ribbon rolled into a cylindrical shape, slightly wider at the top than at the bottom.



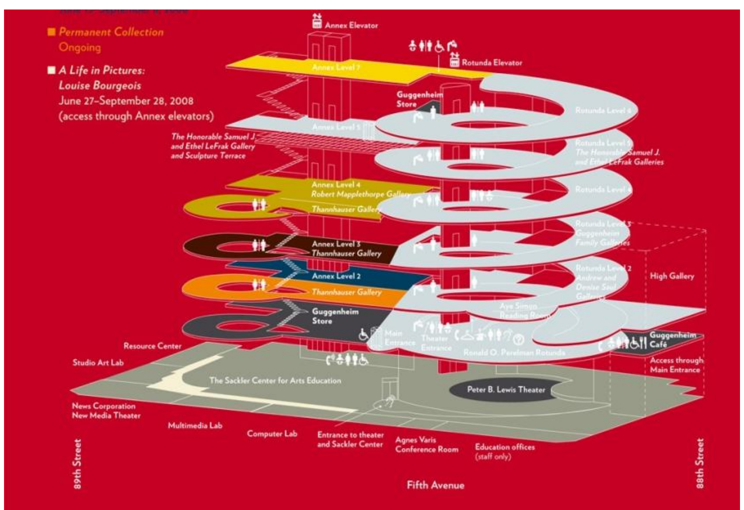
Gordon Strong Automobile Objective and Planetarium (unbuilt) 1924-25

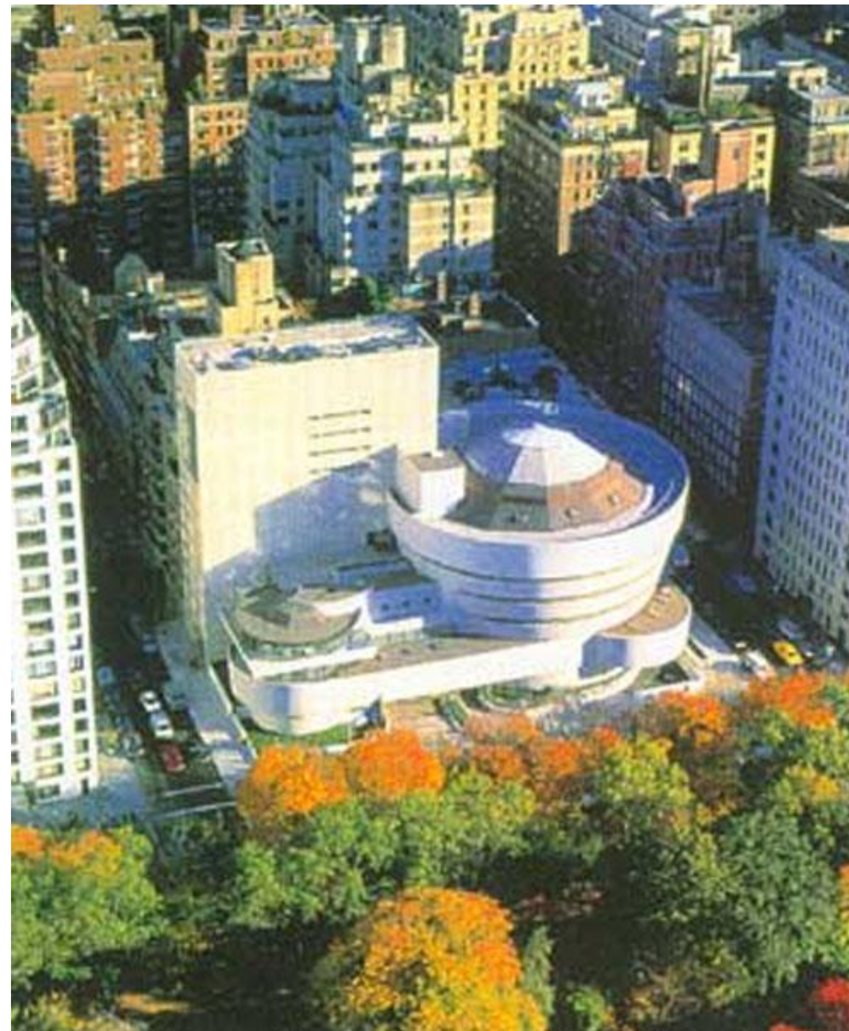


Soloman R. Guggenheim Museum, New York, 1943 - 59

Building Layout: Bridge

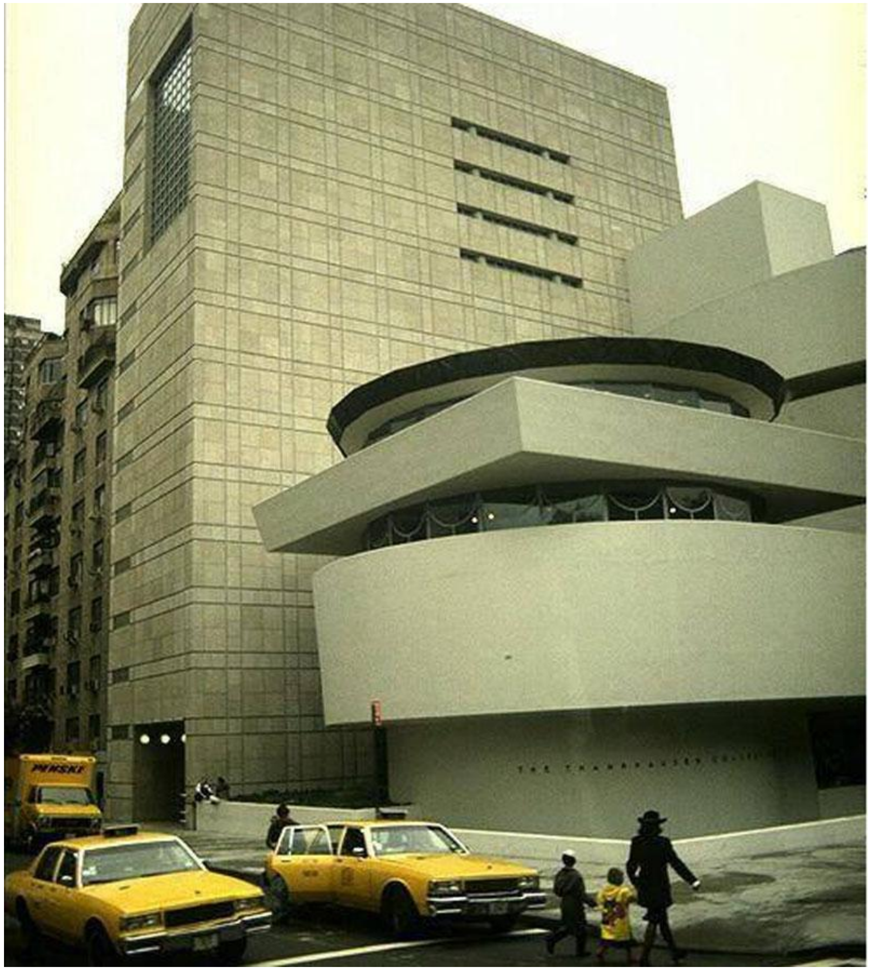
- Connects the monitor and rotunda, used to feature porte-cochere, in which a vehicle drove under the bridge to drop off visitors and provided drive access under the structure. However, in 1975 it was closed off and now houses a bookstore.





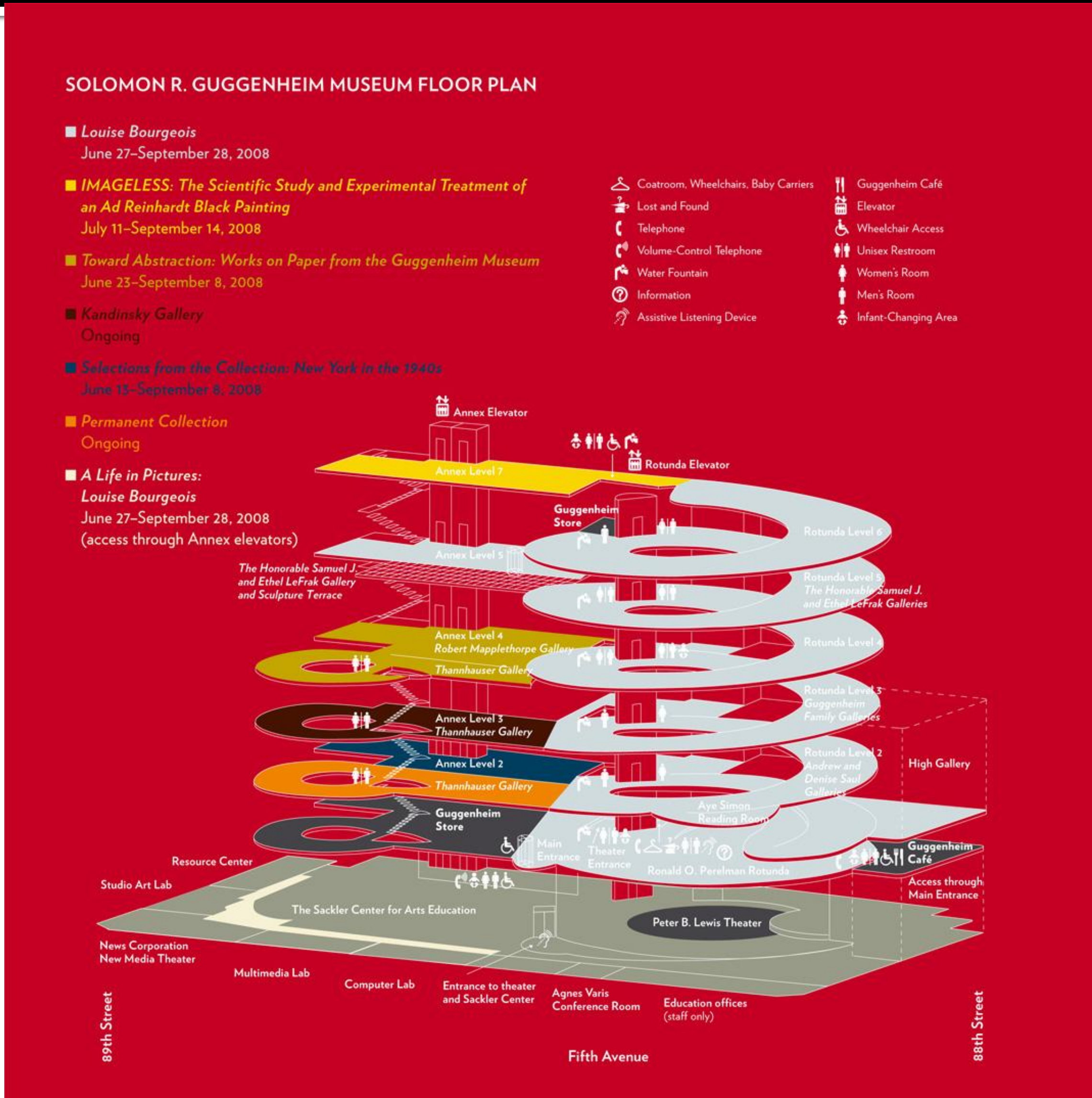
Building Layout: Annex

- Ten story limestone clad.
- Constructed in 1992. It was an extension of the four story annex built in 1968, the present structure occupies the same footprint and incorporates the foundations and framing of its predecessor.
- Four floors of exhibition space, three of which are double height, also has office and storage space for mechanical systems.



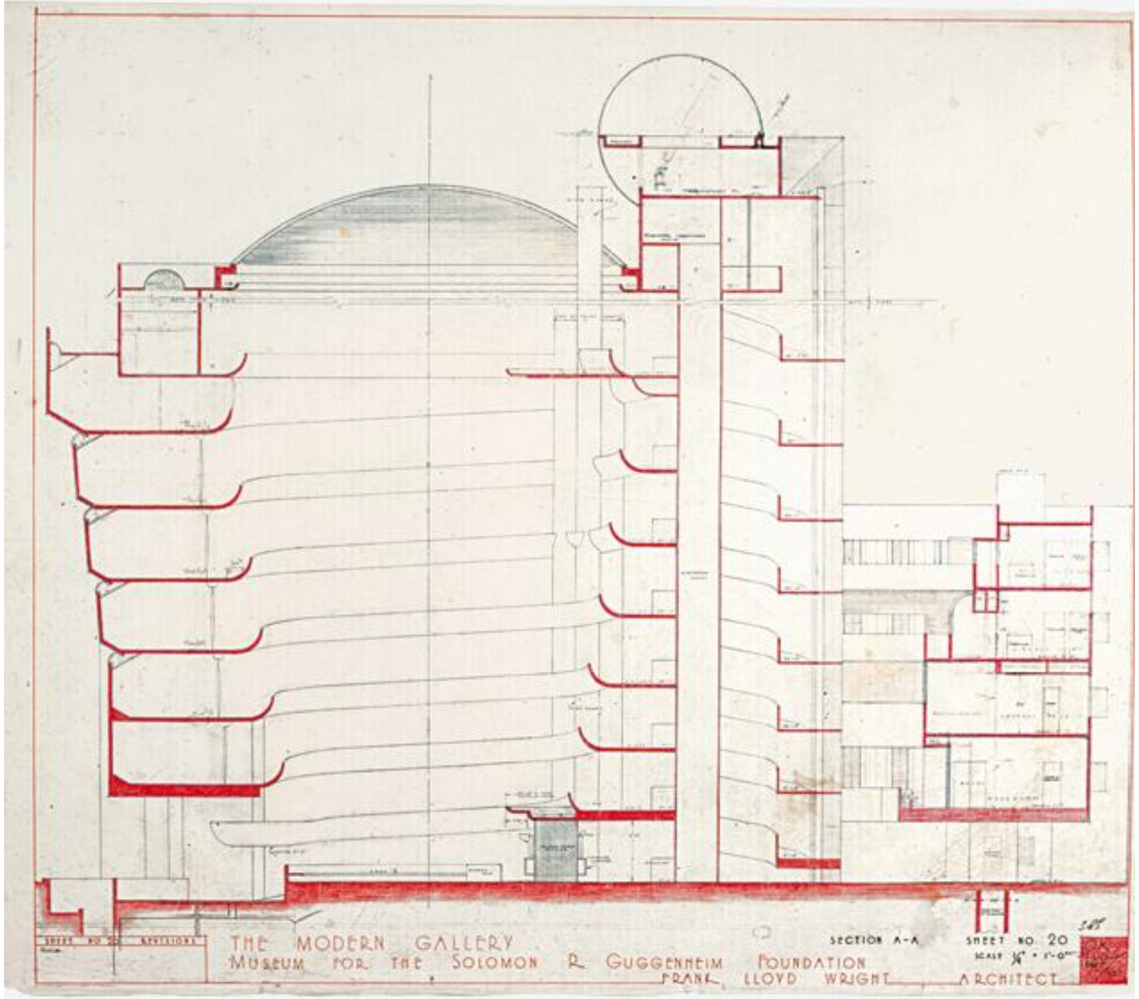
Building Layout: Rotunda

- Twelve radial web walls divide the gallery into 70 bays for viewing artwork.
- A large glass dome covers the entire rotunda, providing natural lighting inside the gallery.
- Skylights line each level of the rotunda, providing natural light along the periphery.
- The gallery walls are 9’6” tall and slope slightly outwards at 97 degrees from the floor.
- Designed to hold paintings, the tilt of the gallery walls was intended to replicate the slope of an easel.



Building Layout: Monitor

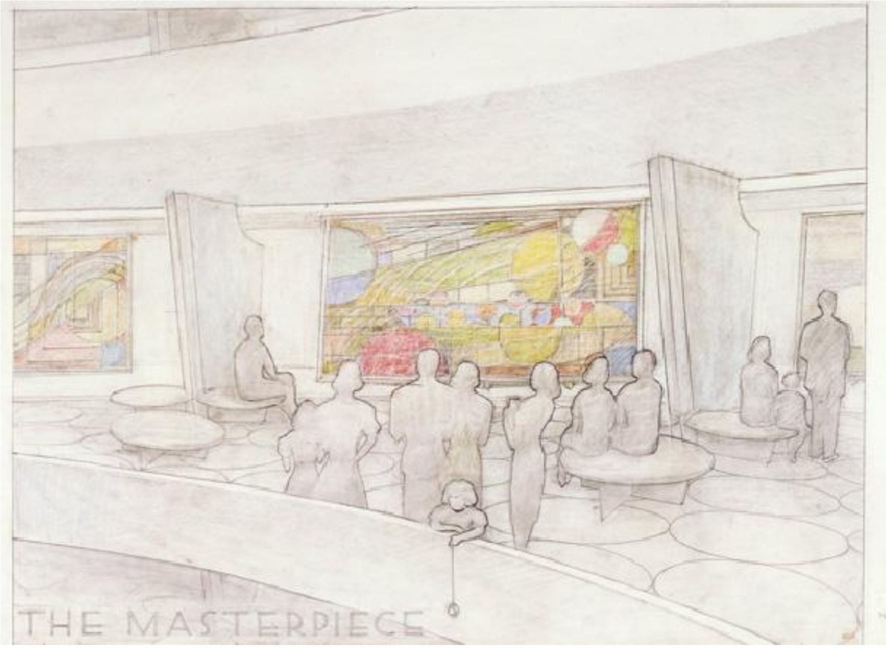
- Originally serviced work spaces, a library, offices, and apartments
- In 1963, the second floor of the monitor was converted into a separate gallery that opens to the main exhibition space.
- In 1980, the monitor's ground floor was opened to the main lobby. All other floors are utilized for gallery space.



Solomon R. Guggenheim Museum, New York, 1943–59. Section (working drawing), 1945. Frank Lloyd Wright Foundation, Scottsdale, Arizona 4305.136

Building Features: Lighting

- skylights: originally intended to illuminate the painting in natural light, but were changed to artificial to have more controlled lighting
- The lower image illustrates the 70 bays that the web walls create

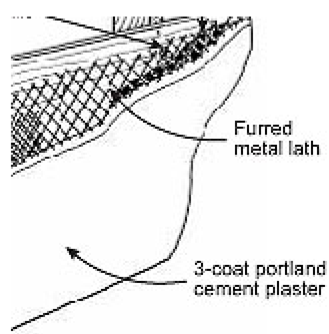


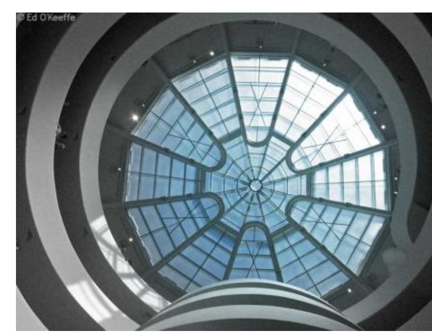
Building Components and System

- Glass dome with aluminum frame
- 12 ribs, coinciding with the 12 radial “web walls”
- The web walls connect at the roof level forming hairpin beams that support the massive central skylight.

Materials

- The Guggenheim is primarily composed of reinforced concrete.
  - Normal weight cast in place concrete is the material of the lower levels.
  - light weight concrete is the material of the interior radial walls and the ramps.
- Gunite, or shotcrete, is the material used for the exterior of the spiral curved walls.
- Wright used gunite to achieve a seamless monolithic façade.
- Wright left out expansion joints, which would have created visual vertical breaks. He hoped the application of elastomeric paint, known as the "cacoon" would fill in the cracks formed during construction.
- The pairing of multiple types of concrete caused visible cracks in the façade.
- Steel framed windows
- Aluminum skylights
- Cement plaster soffits on metal lath.



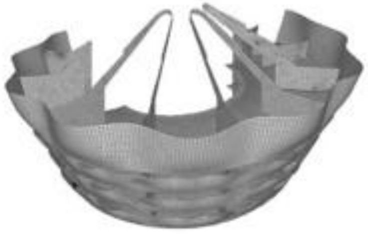


Materials: Gunite

- Gunite (shotcrete): a mixture of concrete and sand that is sprayed through a metal mesh with wooden formwork.
- The reinforcing of the shotcrete consists of vertical and horizontal steel bars sandwiched between two layers of welded wire mesh.
- The curved walls are constructed of shotcrete (gunite) which was sprayed onto plywood forms secured every 10 degrees to vertical steel Tees embedded in the walls.
- Shotcrete walls are 5 inches thick.

Restoration: Technology

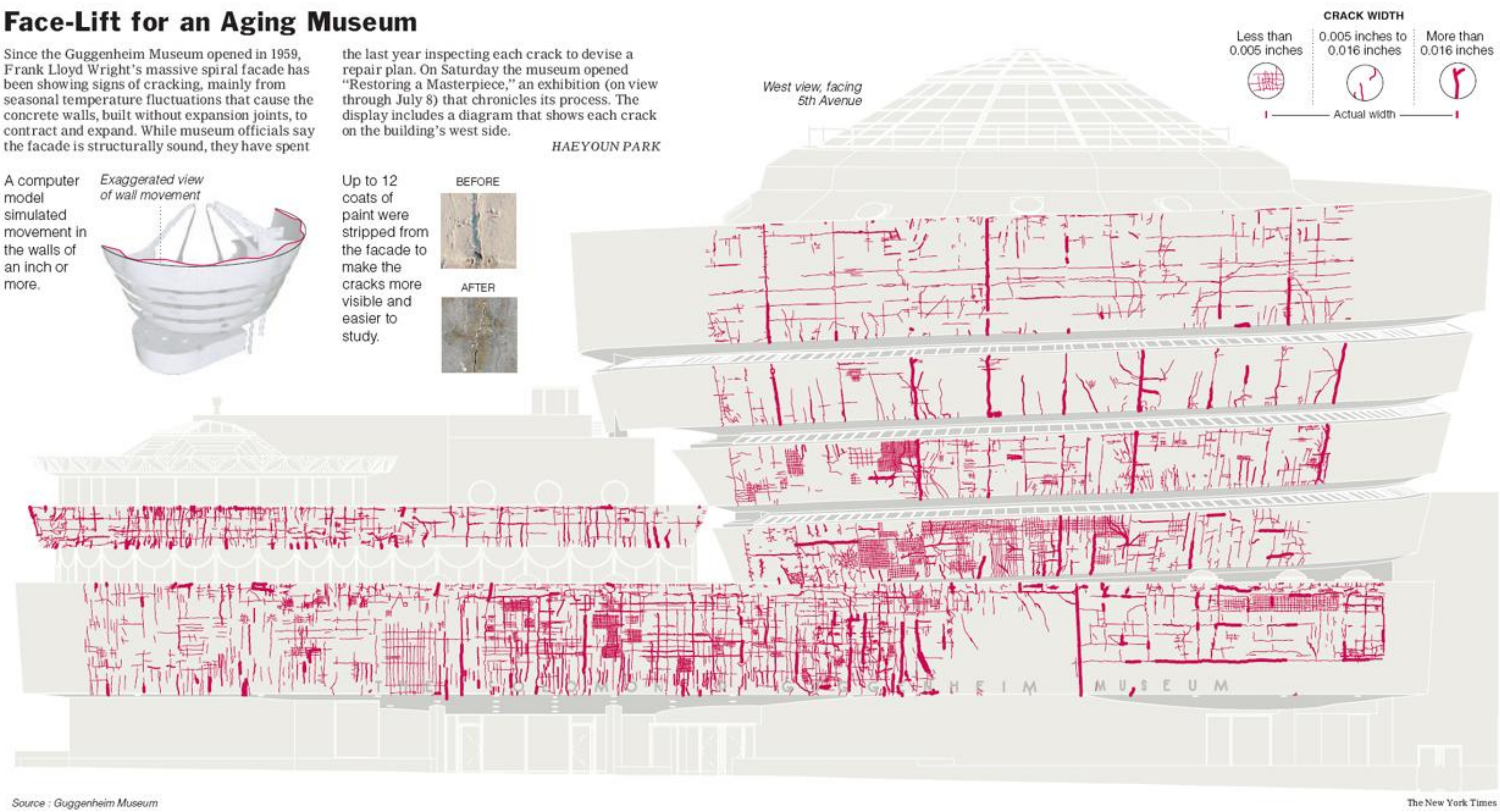
- Used cutting-edge laser-surveying technology
- Even slight variations in the helical ramp and the exterior walls were modeled.
- Analyzed dead, live, wind and, most importantly, temperature loads.
- Indicated a globally stable, dynamic structure; exterior walls move inward and outward under temperature change.
- Only limited structural repairs of the uppermost Rotunda wall were required.



Restoration

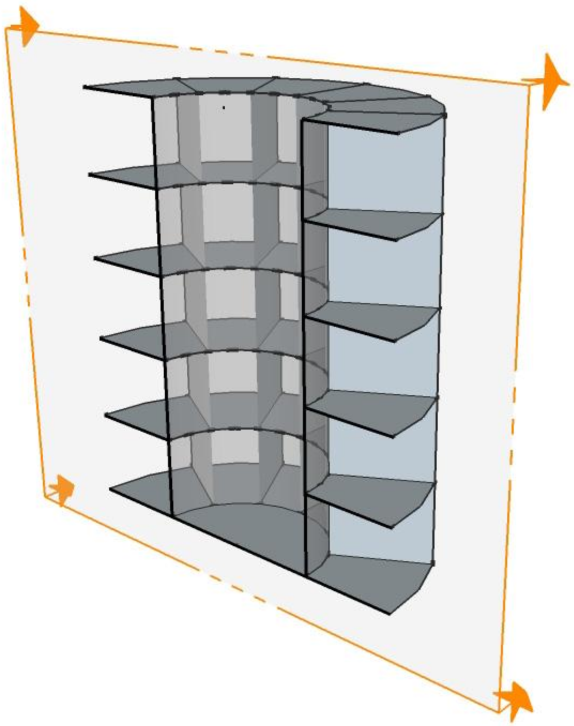
- From December 2004 through September 2008, the Solomon R. Guggenheim Museum underwent its first major restoration.
- The sixth floor ramp walls were structurally reinforced with a basket-weave pattern of carbon-fiber reinforced polymer (CFRP) applied to the interior surface.
- Carbon fiber strips restore tensile capacity to deteriorating ramp walls yet meet architectural aesthetic and preservation requirements.

Restoration: Cracking



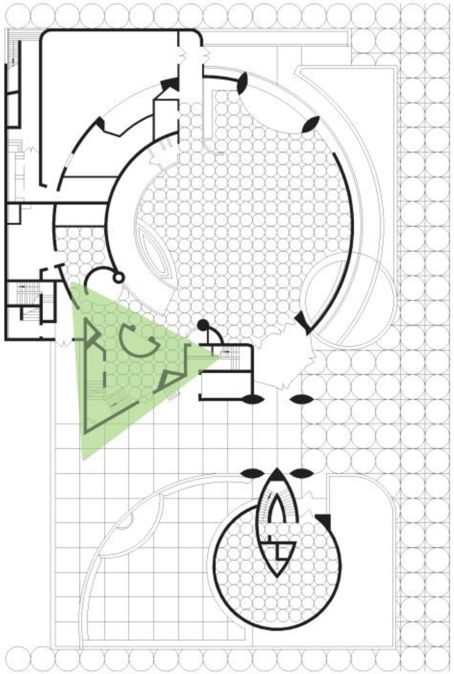
Building Components and System

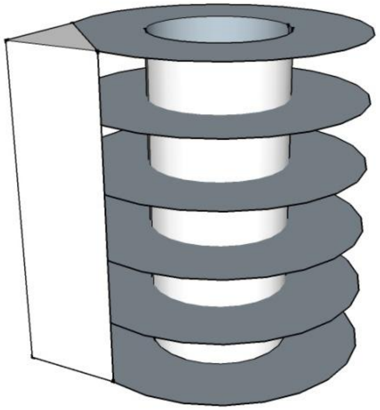
- A giant spiral ramp circulates up to a giant dome with twelve narrow reinforced concrete partitions that pierce the spiral and serve as stiffeners
- The web walls act as shear walls, transferring forces laterally and vertically, while helping resist bending moments.
- 12 radial web walls around the rotunda, 8" thick and 25' wide at the top



Building Components and System

- Structural core that includes staircase and elevator shaft
- Acts as structural anchor and provides an alternate circulation to the ramp





Building Components: Constructed

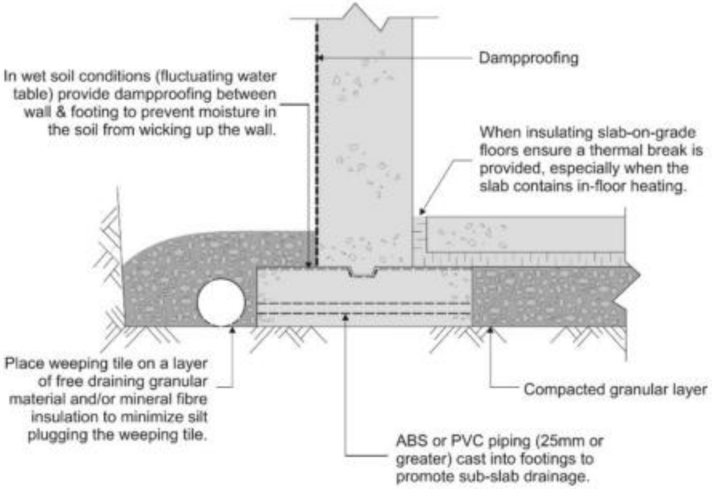
- Cast in place concrete for the floor slab and shear walls; reinforced concrete
- Each ramp section was constructed first then the "web walls" were put in place
- The exterior walls were constructed last by the gunite process

Soil Analysis

- **Parent Material**: Loamy fill, greater than 40 inches deep, high in rock fragments
- **Landform**: Anthropogenic fill areas
- **Depth to Bedrock**: Very deep
- **Drainage Class**: Well drained
- **Permeability**: Moderate, moderately slow where the surface has been compacted
- **Soil Texture**: Silt loam, loam, or sandy loam throughout
- **Coarse Fragments**: 5 to 70 percent rock fragments throughout; less than 10 percent artifacts
- **Range in Soil pH**: Very strongly acid to slightly acid
- **Hydrologic Soil Group**: B

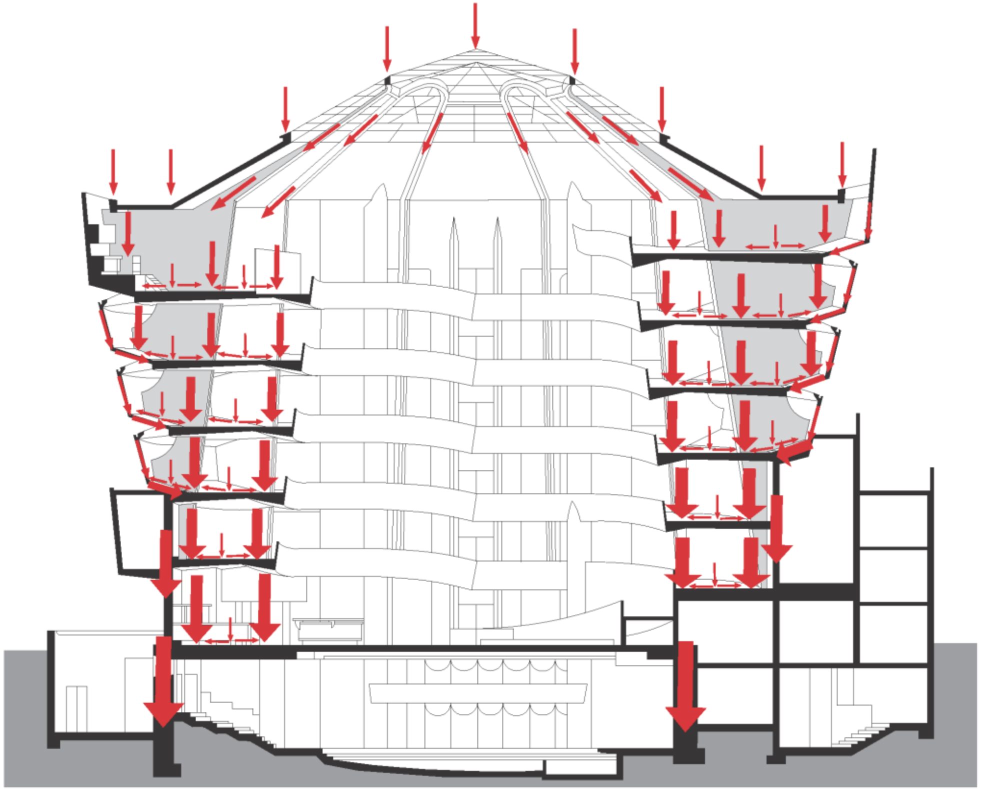
Building Components: Foundation

- Because the soil is easily drained, it allows for an underground level.
- Underground level contains a theater and bookstore which is outlined with thick load-bearing concrete walls.
- There is a deep foundation with a basement wall footing that encloses a basement space and it is restrained by a top floor slab of reinforced concrete.

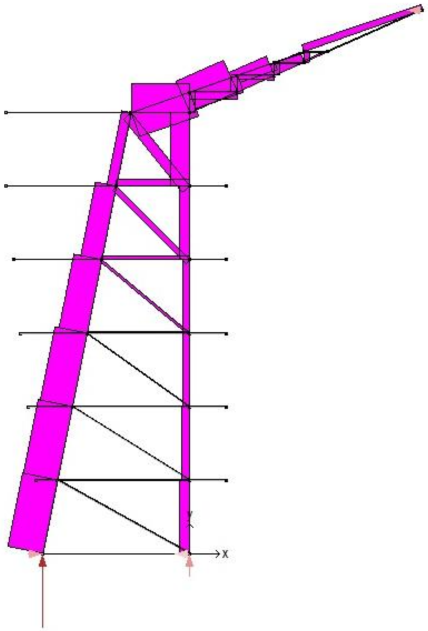


Loading Summary: Gravity Load Tracing

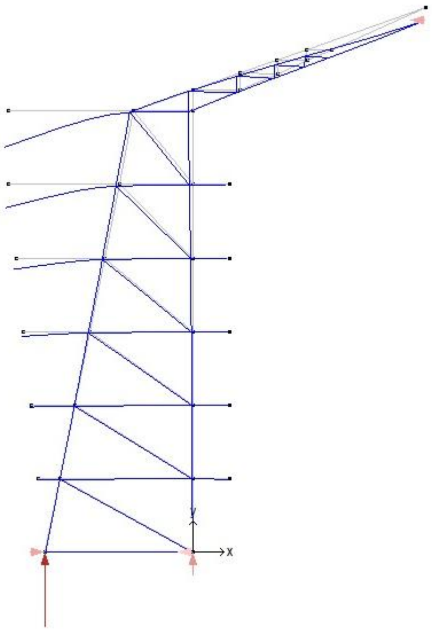
- The loads are transferred from the dome to the hairpin ribs, which then transfer into the web walls.
- The loads from the floor slab and cantilevered angled walls also trace back to the web walls, which act as shear walls and transfer all loads to the foundation.



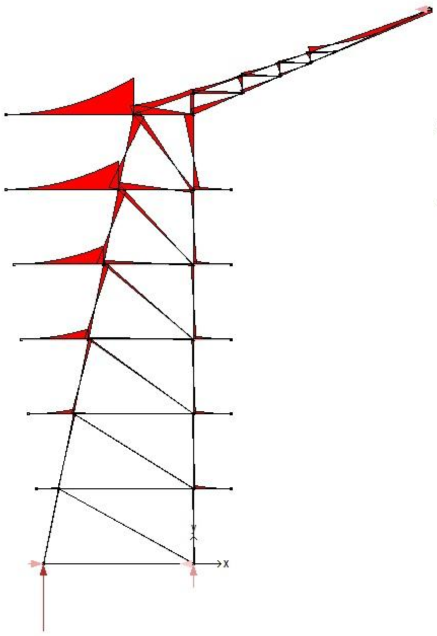
Loading Summary: Gravity Loads



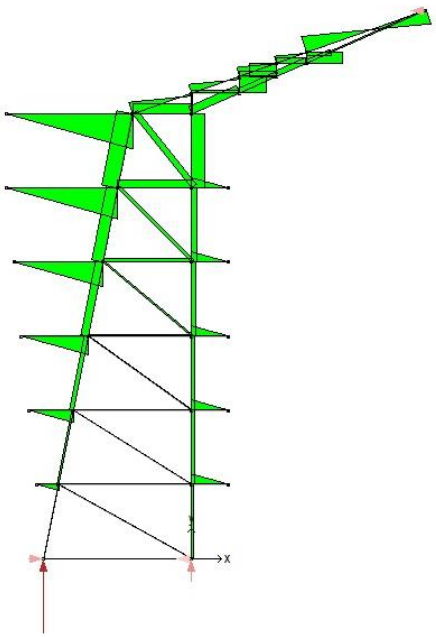
Axial



Deflection



Moment



Shear

- As you can see from this multiframe analysis, the diagrams show that the bending moments are greatest at the top, where the web walls are supporting the glass dome through the hairpin ribs, and the floors cantilever out the furthest.
- The axial forces grow down the structure as each load becomes increasingly greater.

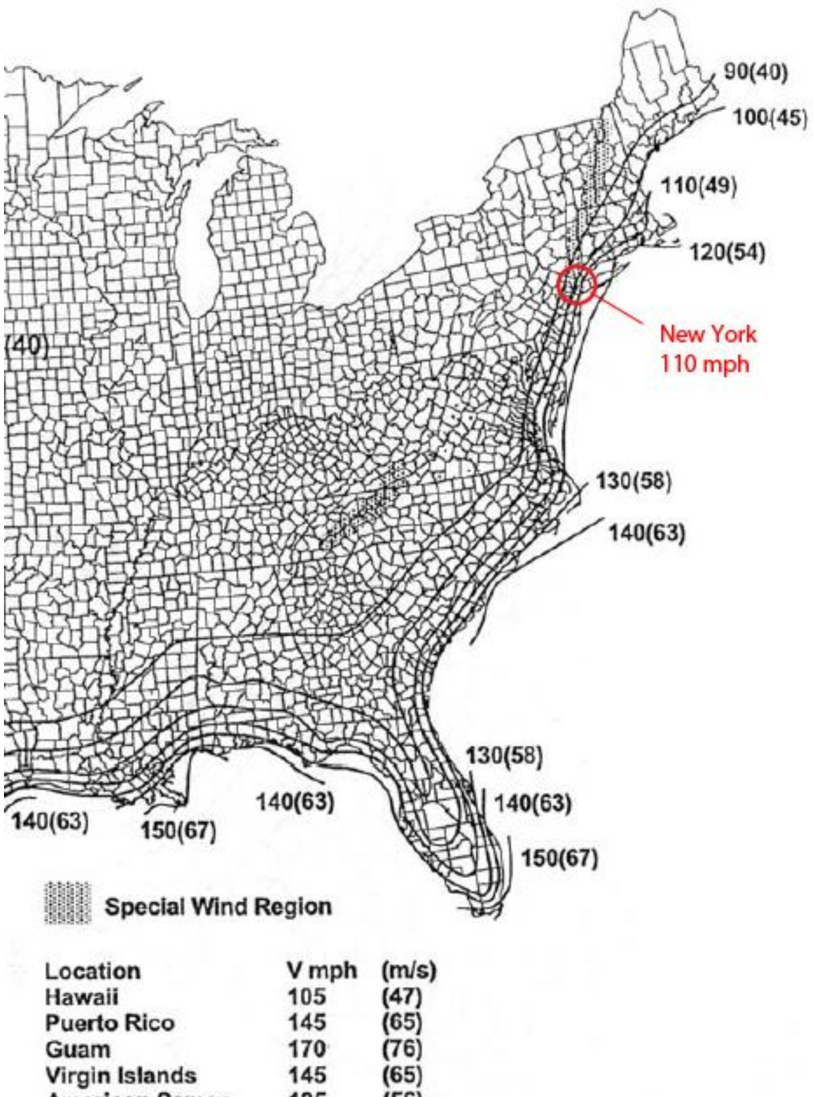
Loading Summary: Lateral Loading

- Wind Region: New York: 110 mph

Main Wind Force Resisting System – Method 1		h ≤ 60 ft.
Figure 6-2 (cont'd)	Design Wind Pressures	Walls & Roofs
Enclosed Buildings		

Simplified Design Wind Pressure, p_{S30} (psf) *(Exposure B at h = 30 ft. with I = 1.0)*

Basic Wind Speed (mph)	Roof Angle (degrees)	Load Case	Zones									
			Horizontal Pressures				Vertical Pressures				Overhangs	
			A	B	C	D	E	F	G	H	EOH	GOH
85	0 to 5°	1	11.5	-5.9	7.6	-3.5	-13.8	-7.8	-9.6	-6.1	-19.3	-15.1
	10°	1	12.9	-5.4	8.6	-3.1	-13.8	-8.4	-9.6	-6.5	-19.3	-15.1
	15°	1	14.4	-4.8	9.6	-2.7	-13.8	-9.0	-9.6	-6.9	-19.3,	-15.1
	20°	1	15.9	-4.2	10.6	-2.3	-13.8	-9.6	-9.6	-7.3	-19.3	-15.1
	25°	1	14.4	2.3	10.4	2.4	-6.4	-8.7	-4.6	-7.0	-11.9	-10.1
		2	------	------	------	------	-2.4	-4.7	-0.7	-3.0	------	------
	30 to 45	1	12.9	8.8	10.2	7.0	1.0	-7.8	0.3	-6.7	-4.5	-5.2
		2	12.9	8.8	10.2	7.0	5.0	-3.9	4.3	-2.8	-4.5	-5.2
90	0 to 5°	1	12.8	-6.7	8.5	-4.0	-15.4	-8.8	-10.7	-6.8	-21.6	-16.9
	10°	1	14.5	-6.0	9.6	-3.5	-15.4	-9.4	-10.7	-7.2	-21.6	-16.9
	15°	1	16.1	-5.4	10.7	-3.0	-15.4	-10.1	-10.7	-7.7	-21.6	-16.9
	20°	1	17.8	-4.7	11.9	-2.6	-15.4	-10.7	-10.7	-8.1	-21.6	-16.9
	25°	1	16.1	2.6	11.7	2.7	-7.2	-9.8	-5.2	-7.8	-13.3	-11.4
		2	------	------	------	------	-2.7	-5.3	-0.7	-3.4	------	------
	30 to 45	1	14.4	9.9	11.5	7.9	1.1	-8.8	0.4	-7.5	-5.1	-5.8
		2	14.4	9.9	11.5	7.9	5.6	-4.3	4.8	-3.1	-5.1	-5.8
100	0 to 5°	1	15.9	-8.2	10.5	-4.9	-19.1	-10.8	-13.3	-8.4	-26.7	-20.9
	10°	1	17.9	-7.4	11.9	-4.3	-19.1	-11.6	-13.3	-8.9	-26.7	-20.9
	15°	1	19.9	-6.6	13.3	-3.8	-19.1	-12.4	-13.3	-9.5	-26.7	-20.9
	20°	1	22.0	-5.8	14.6	-3.2	-19.1	-13.3	-13.3	-10.1	-26.7	-20.9
	25°	1	19.9	3.2	14.4	3.3	-8.8	-12.0	-6.4	-9.7	-16.5	-14.0
		2	------	------	------	------	-3.4	-6.6	-0.9	-4.2	------	------
	30 to 45	1	17.8	12.2	14.2	9.8	1.4	-10.8	0.5	-9.3	-6.3	-7.2
		2	17.8	12.2	14.2	9.8	6.9	-5.3	5.9	-3.8	-6.3	-7.2
110	0 to 5°	1	19.2	-10.0	[illegible]	-5.9	-23.1	-13.1	-16.0	-10.1	-32.3	-25.3
	10°	1	21.6	-9.0	14.4	-5.2	-23.1	-14.1	-16.0	-10.8	-32.3	-25.3
	15°	1	24.1	-8.0	16.0	-4.6	-23.1	-15.1	-16.0	-11.5	-32.3	-25.3
	20°	1	26.6	-7.0	17.7	-3.9	-23.1	-16.0	-16.0	-12.2	-32.3	-25.3
	25°	1	24.1	3.9	17.4	4.0	-10.7	-14.6	-7.7	-11.7	-19.9	-17.0
		2	------	------	------	------	-4.1	-7.9	-1.1	-5.1	------	------
	30 to 45	1	21.6	14.8	17.2	11.8	1.7	-13.1	0.6	-11.3	-7.6	-8.7
		2	21.6	14.8	17.2	11.8	8.3	-6.5	7.2	-4.6	-7.6	-0.7
	0 to 5°	1	22.8	-11.0	15.1	-7.0	-27.4	-15.6	-19.1	-12.1	[illegible]	[illegible]



Loading Summary: Lateral Loading

- Load on side: 14.4 psf

$= 14.4\ lb/ft^2 \times 11458\ ft^2)/ 4$

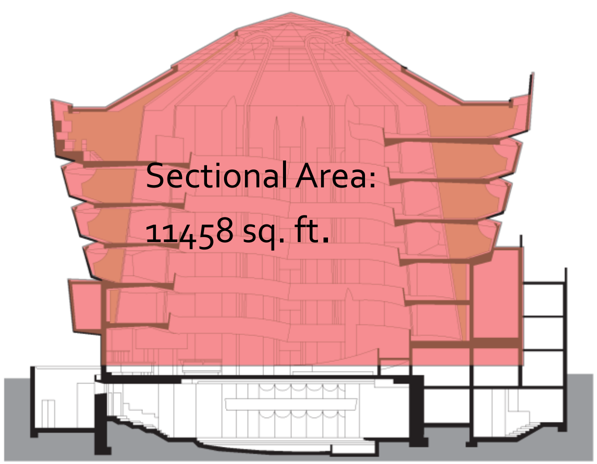
$= 41248.8\ lb$

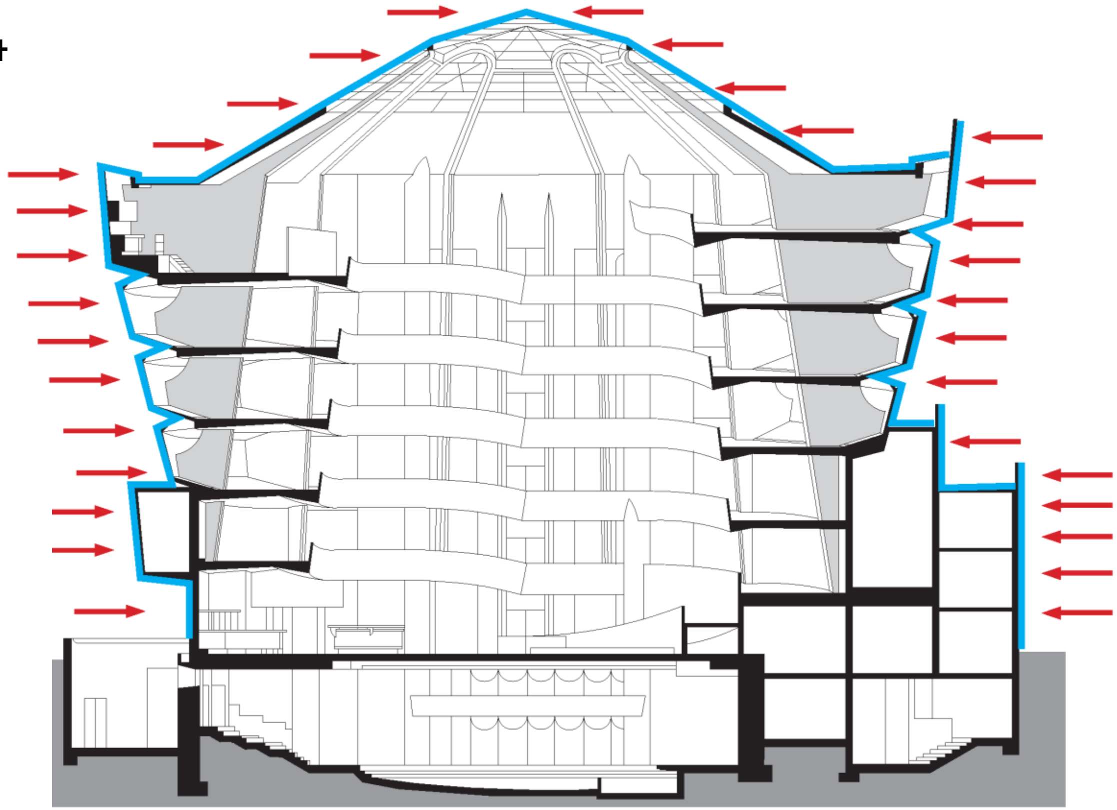
- Distributed Load

Along Edge:

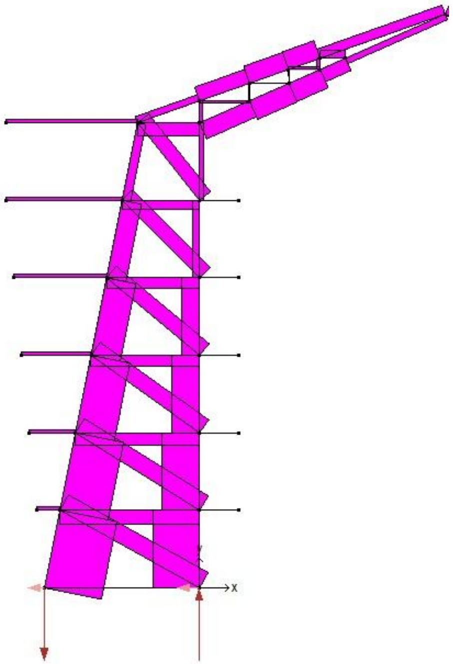
$= 41248.8\ lb/ 142\ ft$

$=290.4\ lb/ft$

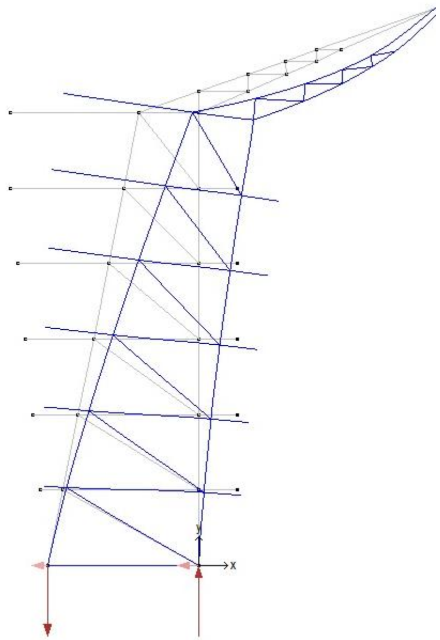




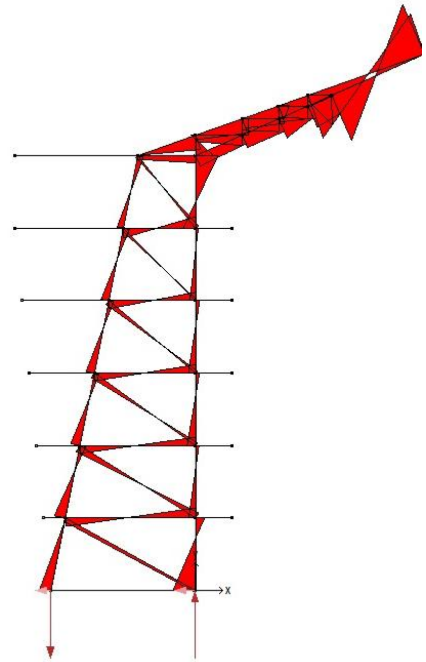
Loading Summary: Wind loads



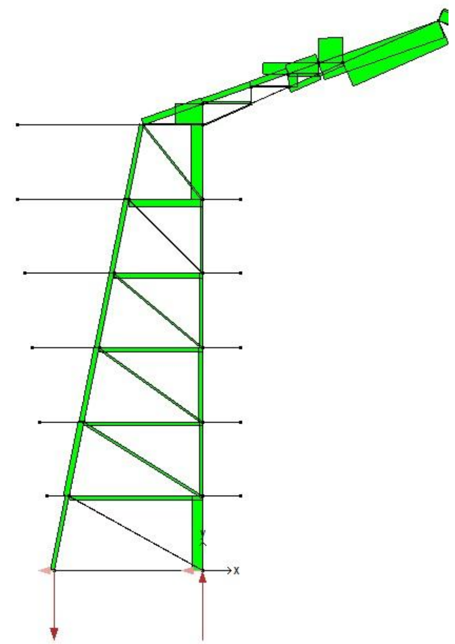
Axial



Deflection



Moment

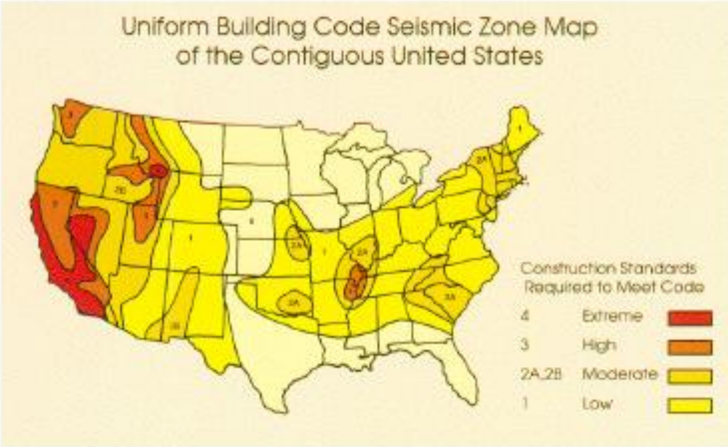


Shear

- The bending moments are highest at the top of the structure. There are also bending moments at the foundation in order to resist the overturning moment.
- The axial forces are great because it is important for the web walls to act as stiffeners and help brace the structure against lateral pressure. Because the rotunda is hallow in the core, the 12 radial web walls provide the necessary bracing to resist the lateral wind loads.

Building Components: Seismic Factors

SUMMARY OF BUILDING CODE SEISMIC DESIGN CONCEPTS		
	Uniform Building Code(1991)	NEHRP Provisions(1991)
Goal	Life Safety	Life Safety
Seismic Load	Base Shear V (F=MA concept) $V = \frac{ZICW}{R_w}$ $(C = \frac{1.25S}{T^{2/3}})$	Base Shear V (F=MA Concept) $V = C_sW$ $(C_s = \frac{1.2A_vS}{RT^{2/3}})$
Zone	Z 5 Zones 0.075, 0.15, 0.20, 0.30, 0.40	6 Zones 0.05, 0.10, 0.15, 0.20, 0.30, 0.40
Import-ance	I Building Occupancy (1.0, 1.25)	SHEG Exposure Groups (3 categories) and SPC Performance Categories (5 categories)
Struct. Response	R_w Response Modifications based on 5 basic Structural types	R Response Modifications based on 6 basic Structural types
Soil	S 4 Soil Profiles (1.0, 1.2, 1.5, 2.0)	S 4 Soil Profiles (1.0, 1.2, 1.5, 2.0)
Mass	W Building Weight	W Building Weight
Period	T Building Period	T Building Period



Zone 2a: Moderate = .15

Occupancy: $I_E = 1.25$

Building Components: Seismic Factors

- Response Modifications: R_w

$R_w = 5.5$

BASIC STRUCTURAL SYSTEM[2]	LATERAL-FORCE-RESISTING SYSTEM DESCRIPTION	R	Ω_o	HEIGHT LIMIT FOR SEISMIC ZONES 3 AND 4 (ft) × 304.8 for mm
1. Bearing wall system	1. Light-framed walls with shear panels			
	a. Wood structural panel walls for structures three stories or less	5.5	2.8	65
	b. All other light-framed walls	4.5	2.8	65
	2. Shear walls			
	a. Concrete	4.5	2.8	160
	b. Masonry	4.5	2.8	160
	3. Light steel-framed bearing walls with tension-only bracing	2.8	2.2	65
	4. Braced frames where bracing carries gravity load			
	a. Steel	4.4	2.2	160
	b. Concrete[3]	2.8	2.2	—
	c. Heavy timber	2.8	2.2	65
2. Building frame system	1. Steel eccentrically braced frame (EBF)	7.0	2.8	240
	2. Light-framed walls with shear panels			
	a. Wood structural panel walls for structures three stories or less	6.5	2.8	65
	b. All other light-framed walls	5.0	2.8	65
	3. Shear walls			
	a. Concrete	5.5	2.8	240
	b. Masonry	5.5	2.8	160
	4. Ordinary braced frames			
	a. Steel	5.6	2.2	160
	b. Concrete[3]	5.6	2.2	—
	c. Heavy timber	5.6	2.2	65
	5. Special concentrically braced frames			
	a. Steel	6.4	2.2	240

Building Components: Seismic Factors

Coefficient A_a= contour map
A_a= .10

Seismic Design Coefficient= C
C= 2.5 A / R

C= (2.5 x .10) / 5.5
C= .04

(the structure will have to be designed to resist lateral forces equal to 40% of its weight.)

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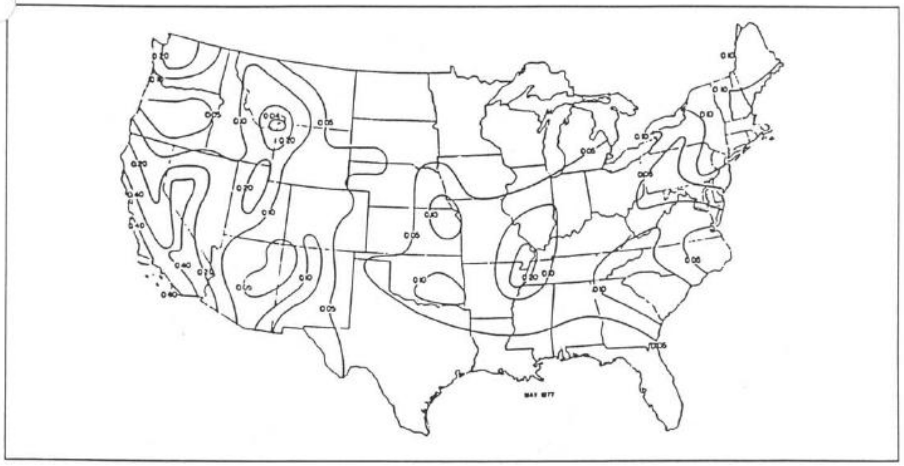

Figure 5.3: Contour map for coefficient A_a for the ›ntinental United States.*

the *equivalent lateral force procedure*. This general methodology is characteristic of all seismic codes throughout the world.

http://www.britannica.com/EBchecked/media/128159/Newsreel-of-the-opening-of-the-Guggenheim-Museum-in-New

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