WILLIS TOWER

ARCH 631- APPLIED ARCHITECTURAL STRUCTURES

Case Study

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Project Background

Location: Chicago, Illinois
Site area: 3 acres
Building area: 4,565,844 sq.ft.
Height: 1450 ft, 1730 ft including twin antennae
Number of stories: 110
Architect and Structural engineers:
SOM (Skidmore, Owings & Merrill)
Year of construction: 1974
Building use: Commercial + office

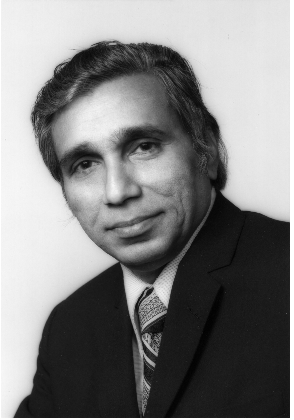
"Willis Tower." *The Skyscraper Center*, www.skyscrapercenter.com/building/willis-tower/169.

Architects

- **Skidmore, Owings and Merrill Architects -** Eminent corporate builders.
- **modernist design** and **sophisticated engineering**.
- **Bruce Graham**'s buildings - bold and muscular interpretation of the Miesian glass box.
- The structural engineer, **Fazlur Khan** - “tube concept” for high rise building design

"Sears Tower was the last supertall building constructed during the International architecture period, and SOM's interpretation of the style is remarkably bold and awe-inspiring."

Bruce Graham



Fazlur Khan

Timeline

1968 Sears group decides to build their headquarters

1970 Ground breaking and sub structure

1971 Super structure construction

1974 Construction completed

Unique aspects

- **Bundled tube** design
- **Observation deck** at the 103rd floor:
  - 1.3 million tourists per year
  - Elevator soars up to the observation deck in 60 seconds
  - Swaying experienced on a windy day
  - Retractable glass boxes protrudes out 4 feet
- The highest skyscraper that uses **only steel structure**. Others use composite construction material (concrete and steel)

"View Chicagoland from the Perch of Willis Tower's Skydeck." *TripSavvy*, TripSavvy, www.tripsavvy.com/willis-towers-skydeck-1492254.

Political Background

- **Naming rights:**
    - Named ‘Sears Tower’ when built by Sears
    - Changed to ‘Willis Tower’ on July 16, 2009 by Willis Group Holdings, Ltd.
    - Naming rights valid for 15 years
- **Major tenants:**
    - United Airlines - 20 floors
    - Willis Group
    - Law firms of Schiff Hardin and Seyfarth Shaw
    - Morgan Stanley (4th largest tenant by 2020)

Program and Function

Design Phase

Sears was the biggest retailer. So, its headquarters had to be **BIG.**

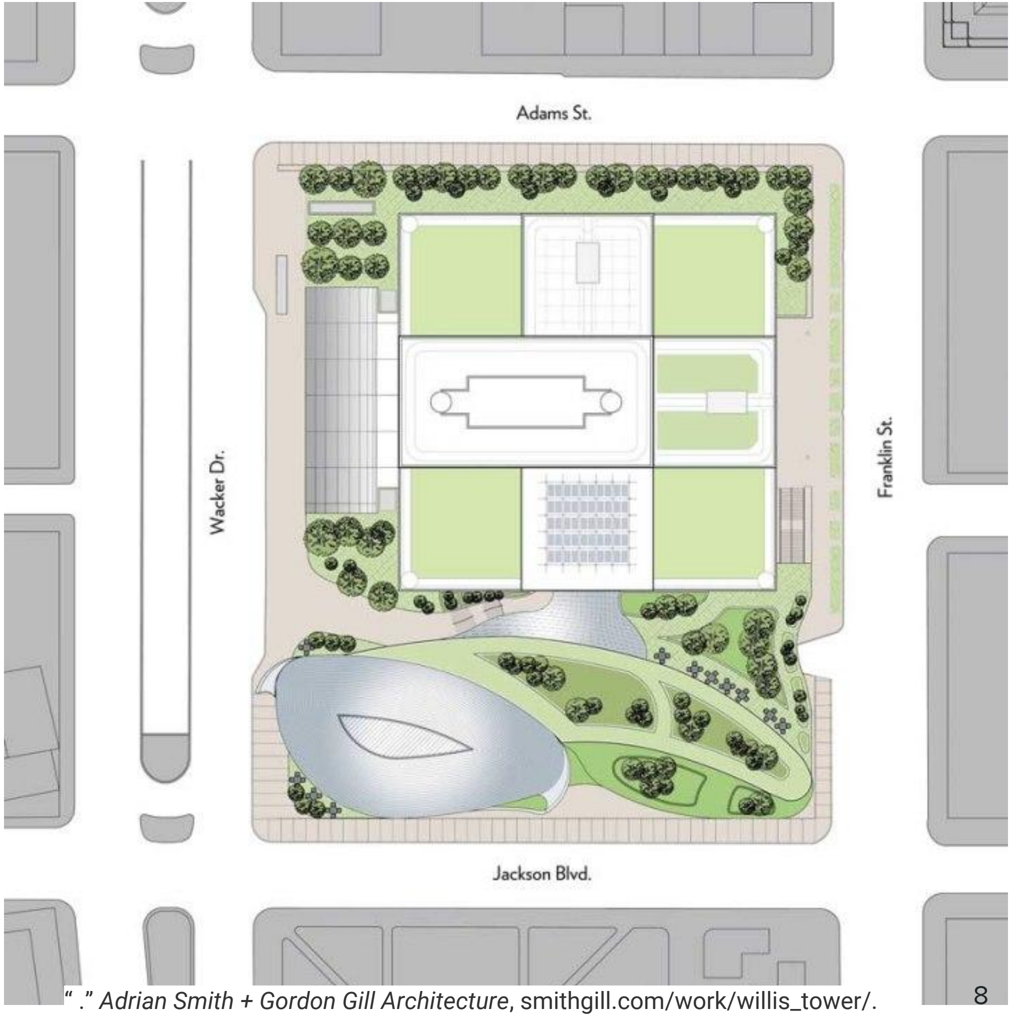
- Offices
- Primary dining club
- Conference facilities
- U.S. Post office
- Retail stores
- Restaurants
- 796 labs

They were only looking to occupy half the building. The upper half was leased to tenants.

Site

- **3 acres**
- Public transportation - access to suburban railroads and bus network.

The Quinzey street ran through the selected site. For $2.7 million, Chicago sold that section of Quinzey street to sears.



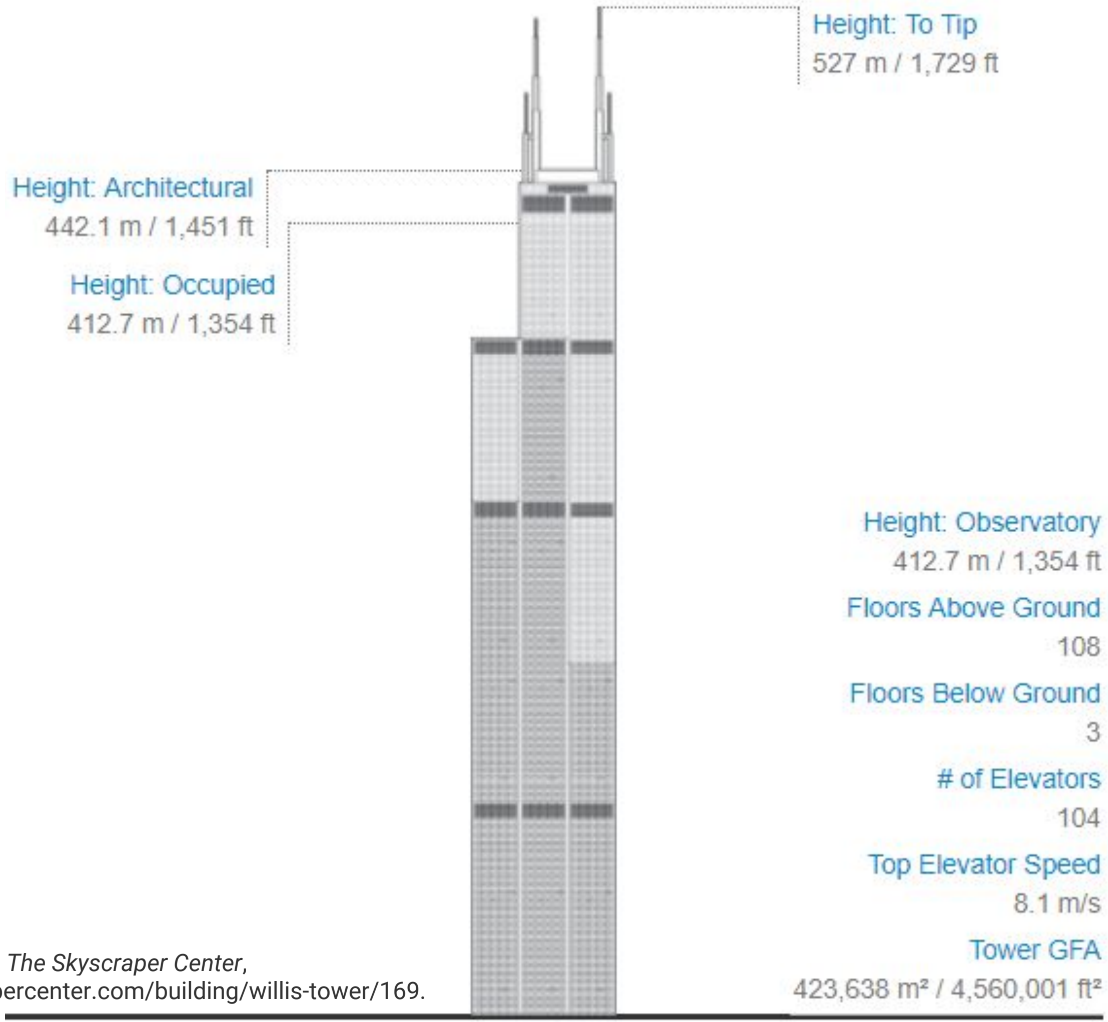
" ." *Adrian Smith + Gordon Gill Architecture*, smithgill.com/work/willis_tower/.

Building Height

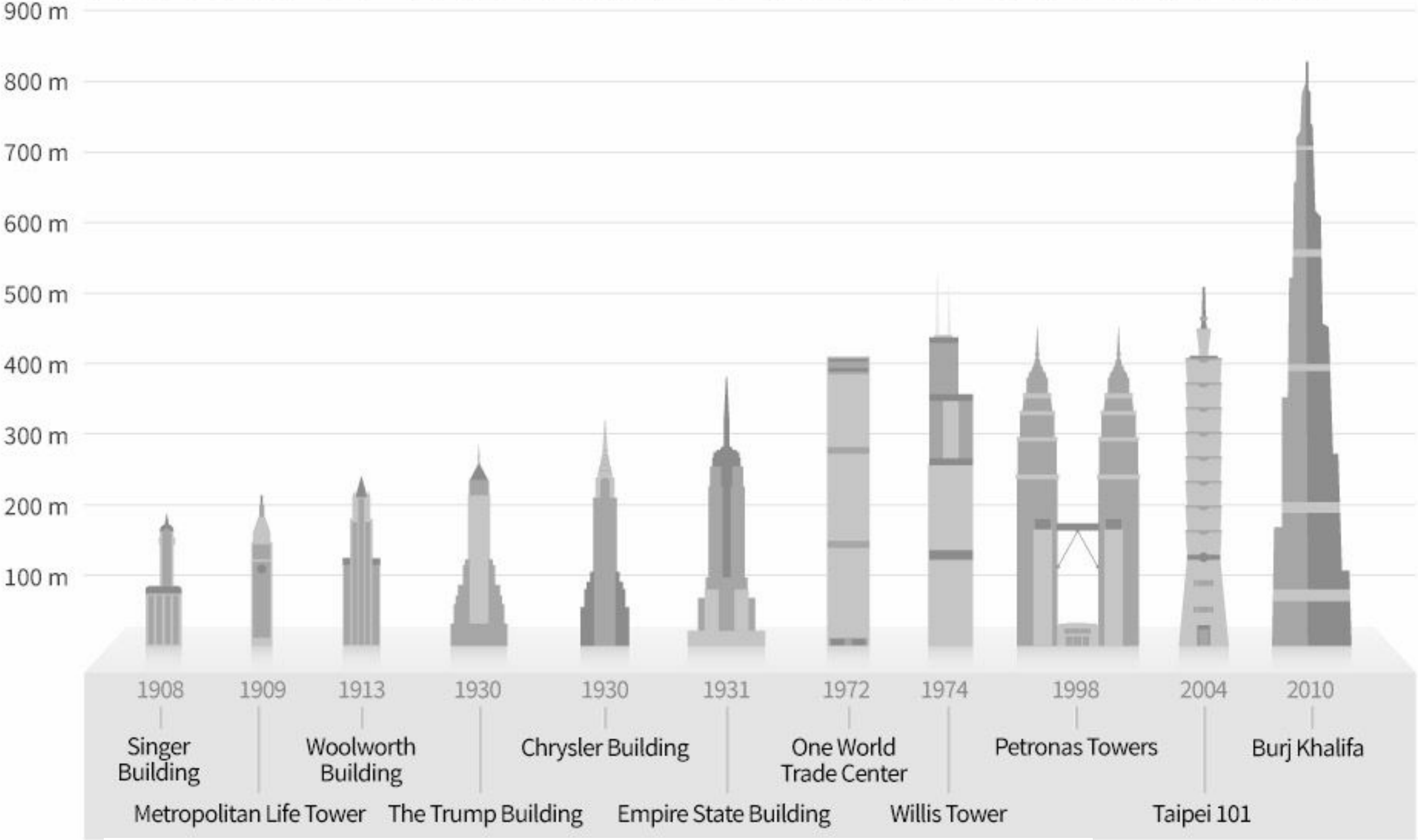
The building construction is completed in 1974, it remained the tallest tower in the world for 25 years.

Now:

- Global Ranking #17 Tallest in the World
- National Ranking #2 Tallest in United States
- City Ranking #1 Tallest in Chicago



"Willis Tower." *The Skyscraper Center*, www.skyscrapercenter.com/building/willis-tower/169.



GmbH, Emporis. “Emporis.” *Buildings | EMPORIS*, www.emporis.com/statistics/history-of-worlds-tallest-buildings.

Building Codes

- Revised the zoning ordinance
  - allowed a building height to be sixteen times the area of the lot.
- Due to cracks and window blowouts caused by extremely high winds in 1988, renovations were made to bring the building up to code during the 1990s.

Materials

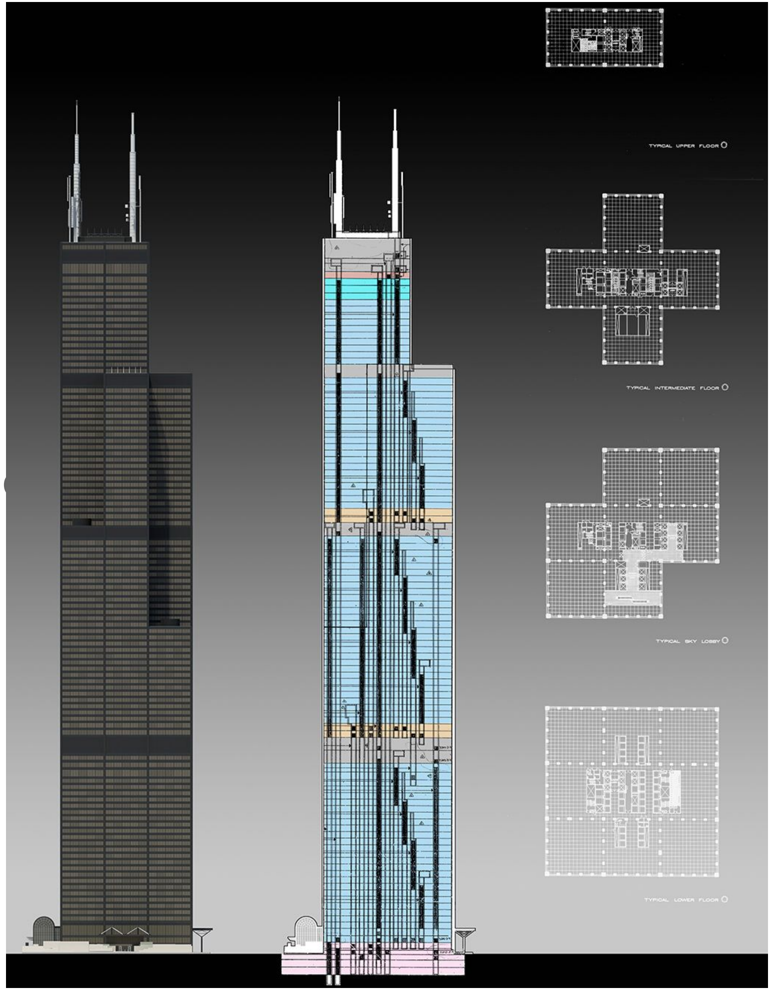
- Structural steel
- Cladding : black aluminium structure and bronze tinted vision glass panels
  - allowed natural lighting of the building and views from all exterior walls
  - Acts as insulation between exterior and interior, maintaining a relatively constant temperature, which helps in minimizing the expansion and contraction of the frame.

http://www.aviewoncities.com/buildings/chicago/searstower.htm

Structural system

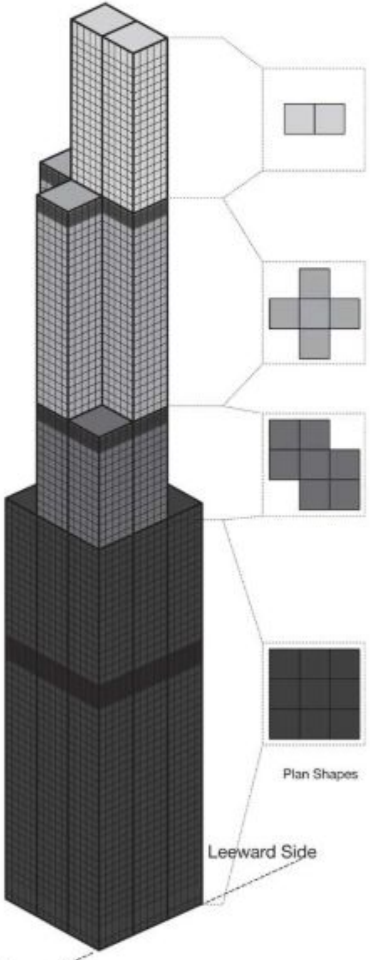
Structural system

- **Tube** construction
- Internal support columns and bracing.
- The frame system is not efficient for larger heights due to large quantity of steel required.
- Khan used the perimeter tube structures instea of a central core.



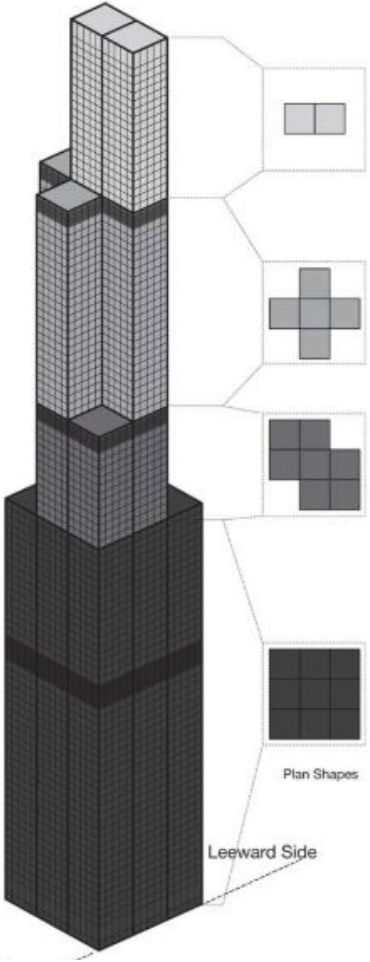
https://www.som.com/projects/willis_tower_formerly_sears_tower__structural_engineering

- Bundled tubes
- The first building to use tube design
- Staggered effect
- Advantages



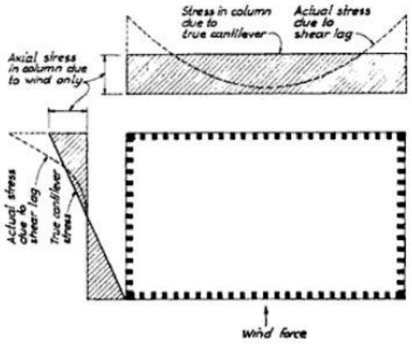
“Skyline Stories | Willis Tower: Windy City Challenge.” *SOM*, www.som.com/ideas/videos/skyline_stories__willis_tower_windy_city_challenge?fbclid=IwAR0pKhqTg07hPSothW4CarQ1TNRd8PUqCPHnWRh6_M5duH0Mnr-szWkE26A.

- Made of nine, 75 ft x 75 ft (22.9 m × 22.9 m) square steel tube units
- The tubes are clearly visible from the exterior of the building

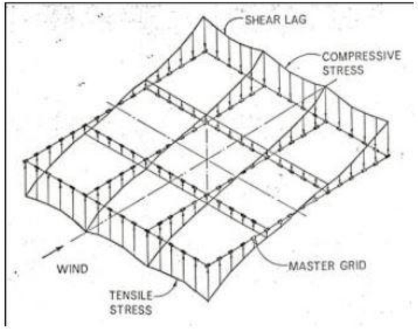


“Skyline Stories | Willis Tower: Windy City Challenge.” *SOM*, www.som.com/ideas/videos/skyline_stories__willis_tower_windy_city_challenge?fbclid=IwAR0pKhqTg07hPSothW4CarQ1TNRd8PUqCPHnWRh6_M5duH0Mnr-szWkE26A.

- Due to the structures height-to-width ratio, a single framed tube is not adequate
- Shear lag
- Bundling tubes increases strength



Shear lag of typical building



Reduced shear lag of Willis Tower

"Truth in Tall Buildings." Princeton University. http://khan.princeton.edu/463.pdf

- Exterior columns act as a wall
- Reduce needs of massive columns in the building interior.
- This column design was used in the Hancock building as well as the World Trade Center.

MSFTV3. YouTube. July 10, 2015. Accessed November 23, 2018. http://www.youtube.com/watch?v=_rm1GiS6Rjc.

Service floors

- Floors 29-33
- Floors 64-66
- Floors 88-90
- Floors 104-109

Hidden floors can be accessed by service elevators only.

The challenge it imposes is the high structural load.

https://hum3d.com/3d-models/willis-tower/

Substructure: Foundation

- **Three foot thick wall** dug around the perimeter of building site.
- **Bentonite Clay Slurry** poured into excavation panels to **prevent ground collapse and infiltration.**
- The **excavation panels** reached approximately 5 stories into the ground.
- With concrete foundation wall in place, the entire site was **excavated to 50 feet**.

MSFTV3. YouTube. July 10, 2015. Accessed November 23, 2018. http://www.youtube.com/watch?v=_rm1GiS6Rjc.

Substructure: Foundation

- **114 reinforced concrete caissons** of varying diameter (6ft - 10ft) were dug another 50’ into the earth.
- **Drilled shafts go to the bed rock** due to heavy loads.
- **Steel jackets** filled with concrete is located under each column.
- A **5 foot concrete matt** was poured at the bottom of the excavation site which tied all caissons together and became **the bottom level of the sears tower**.

MSFTV3. YouTube. July 10, 2015. Accessed November 23, 2018. http://www.youtube.com/watch?v=_rm1GiS6Rjc.

Super structure

- Columns and half of the girders were welded offsite on the fabrication plant.
- **Prefabricated** tree units were brought to site to be raised and bolted together.
- Every piece was numbered
- Iron workers accomplished 2 floors a week.

Floors: In a tubular or bundle system, it is difficult to equally distribute the gravity load of both dead and live loads. So, every 5 floors the **framing is rotated by 90 degrees**.

Structural Elements

- Independently strong
- **Truss connections**
- **Spandrel beams**
- Trussed levels also contain mechanical systems
  - Hidden in facade
  - Louvres mask the structural details

http://www.thesearstower.com/building-information/history-and-facts/

https://en.wikiarquitectura.com/building/sears-tower-willis-tower/#lg=1&slide=27

Interior beams and columns

- Trusses receive gravity load
- X bracing prevents deformation and adds stiffness.
- Steel columns (height of 2 floors)
- Girders welded on center
- RCC floor slabs
- 3.3’ deep trusses

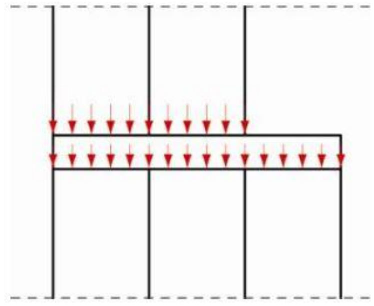


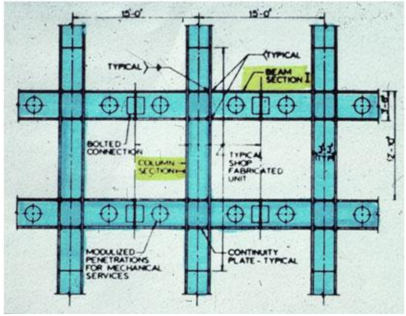
Figure 4. Gravity load transfer through belt truss

"Truth in Tall Buildings." Princeton University.http://khan.princeton.edu/463.pdf

X- bracing at mechanical floors

file:///C:/Users/User/Downloads/som_structural_brochure_web.pdf

file:///C:/Users/User/Downloads/som_structural_brochure_web.pdf



Prefabricated beam-column module

http://khan.princeton.edu/khanSears.html

Lateral wind loads

- The structure acts like a cantilevered tube
  - Moment of inertia
- Traditional building codes could not be used
  - Chicago Building code
  - wind tunnel testing
  - computer aided design
  - statistical analysis

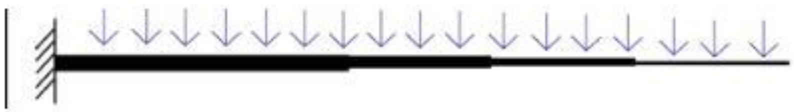
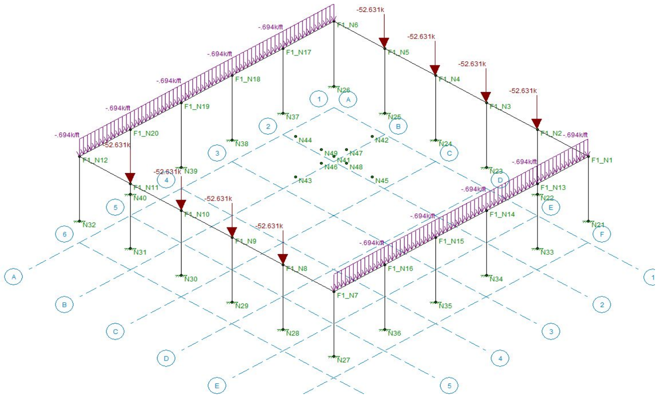
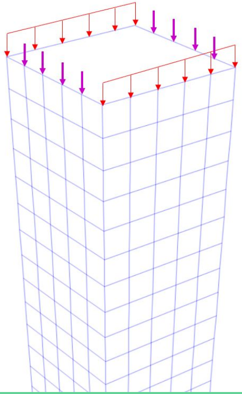


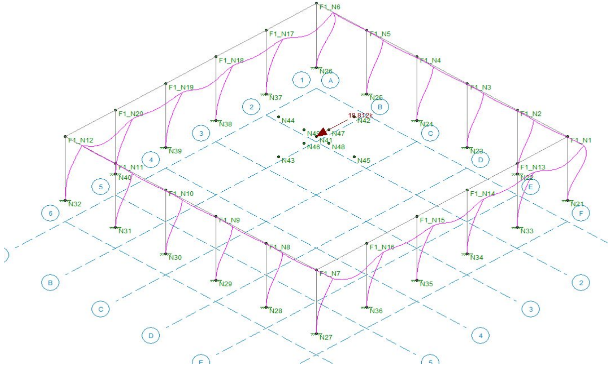
Figure 5. Cantilever Beam Model for Wind

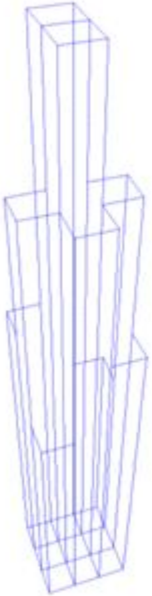
"Truth in Tall Buildings." Princeton University.http://khan.princeton.edu/463.pdf

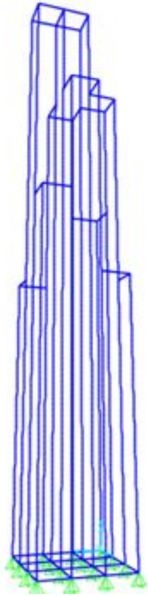
Structural Analysis

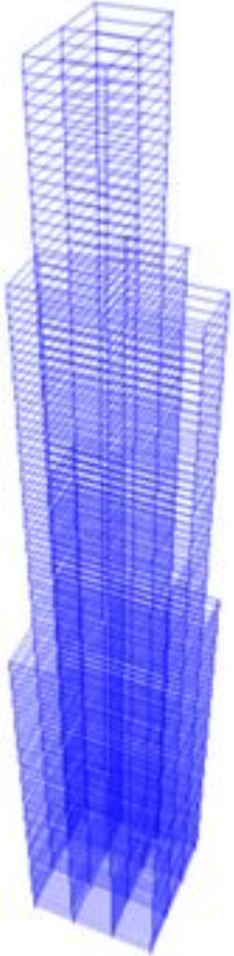










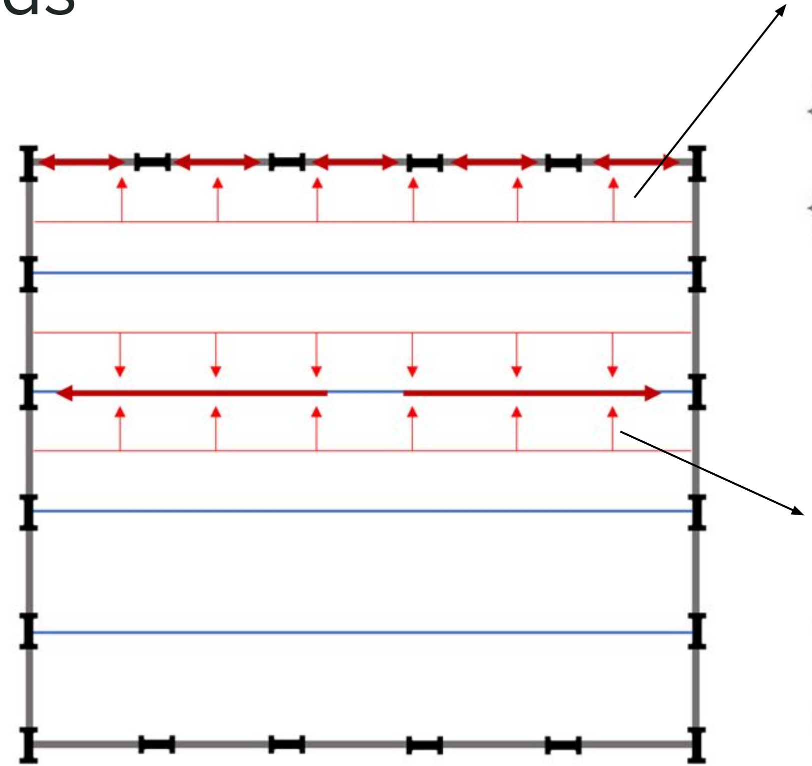


Gravity Loads

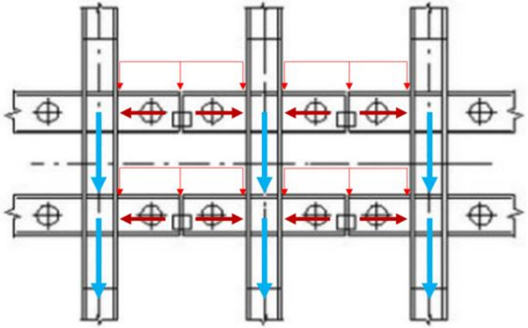
L =50psf (office)
+20psf (partition)

D =20psf

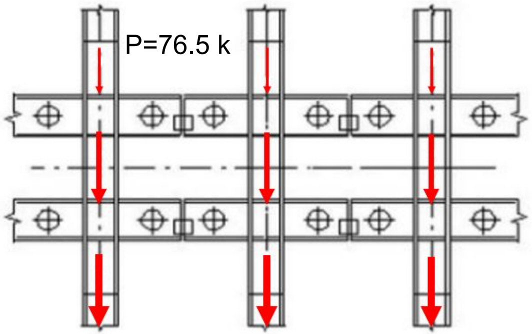
Trib width =15 ft



Slab → Girder → Column



Slab → Beam → Column

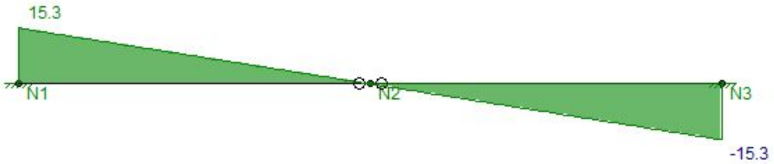


Typical Girder (Interior)

1.2D+1.6L

wu=2.04 k/ft

Shear (kips)

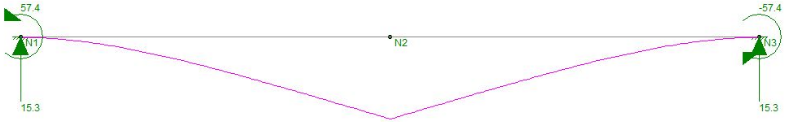


Vu=15.3 k

Moment (k-ft)

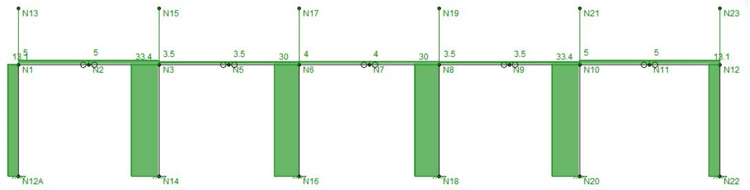
Mu=57.4 k-ft

Deflected Shape



Typical Span

Axial

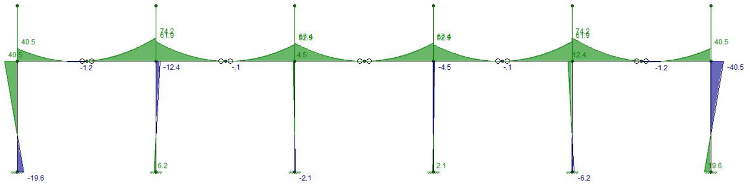


A_col=33.4 k

Shear

V_beam=17.5 k

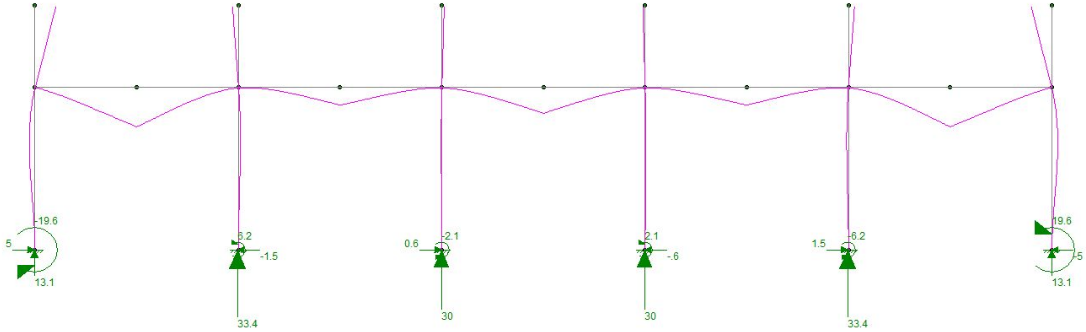
Moment



M_beam=74.2 k-ft

M_col=40.5 k-ft

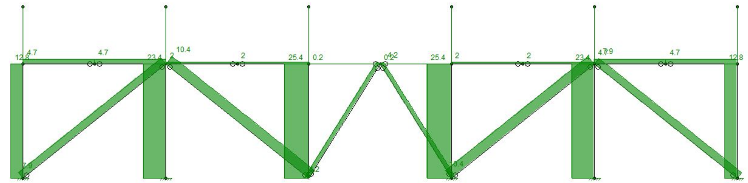
Deflected Shape



Joint Label	X [k]	Y [k]	MZ [k-ft]
N12A	5.006	13.05	-19.575
N14	-1.548	33.448	6.183
N16	.553	30.002	-2.148
N18	-.553	30.002	2.148
N20	1.548	33.448	-6.183
N22	-5.006	13.05	19.575

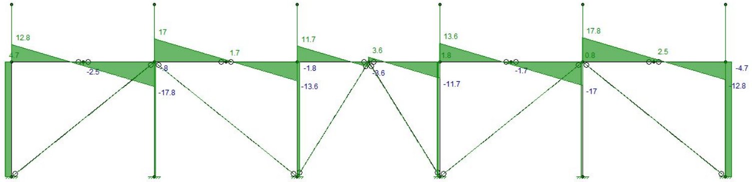
Typical Span w/ Diagonal Bracing

Axial



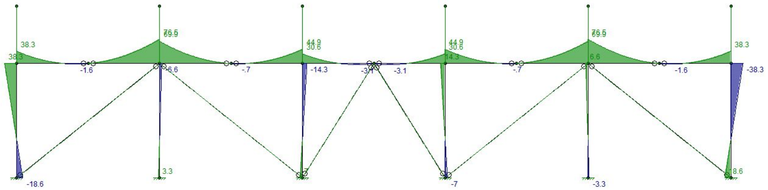
A_col= 25.4 k

Shear



V_beam 17.8= k

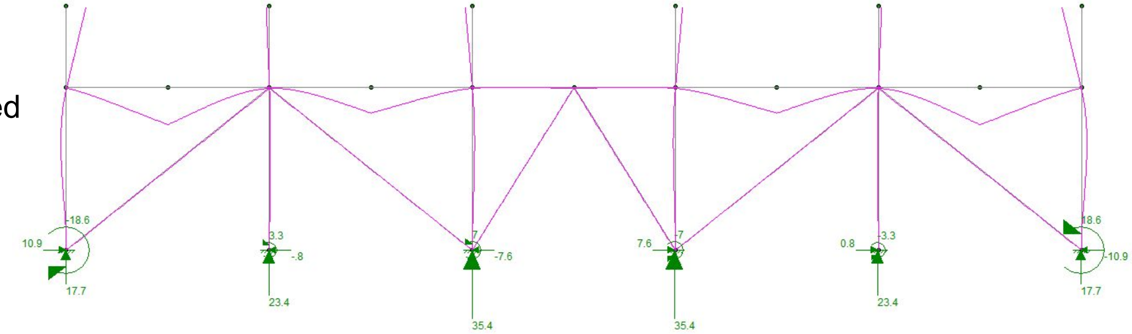
Moment



M_beam= 76.5k-ft

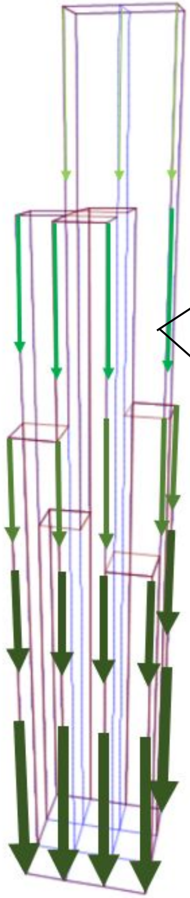
M_col= 38.3 k-ft

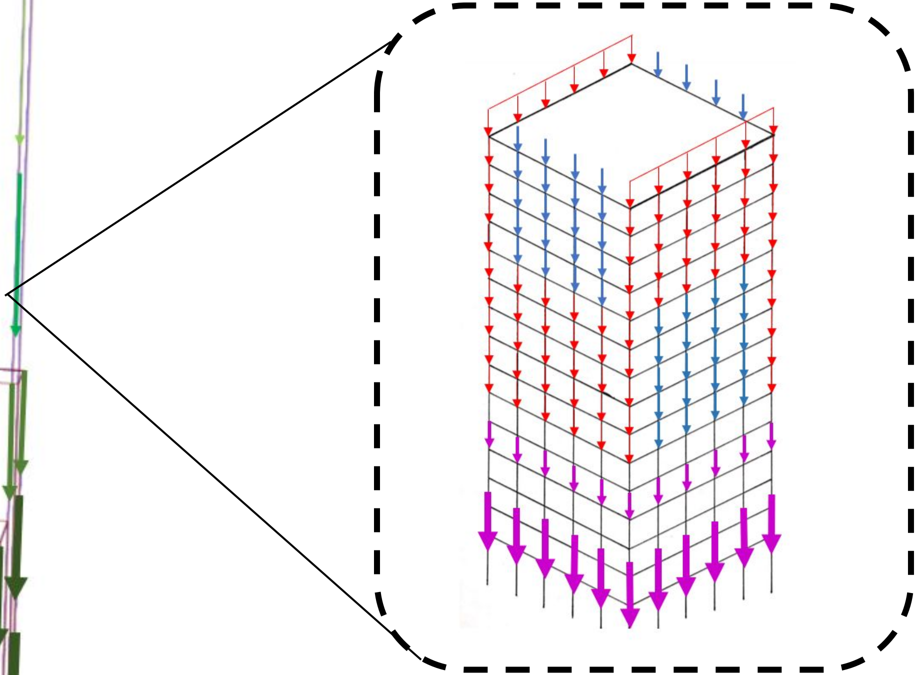
Deflected Shape



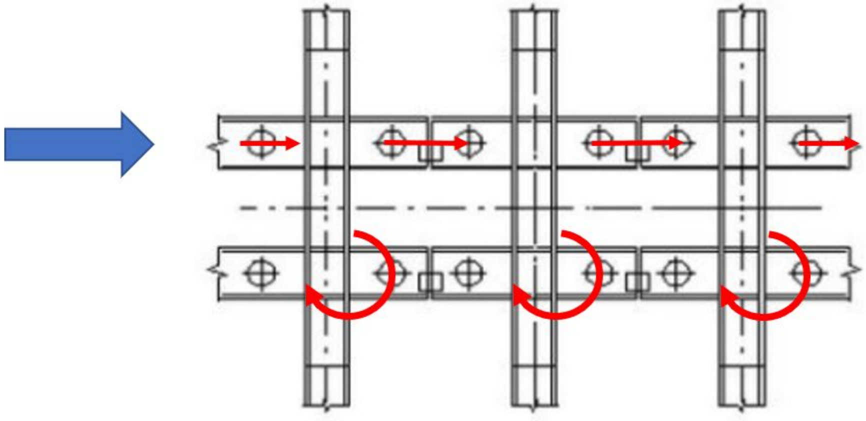
Joint Label	X [k]	Y [k]	MZ [k-ft]
N12A	10.891	17.677	-18.577
N14	-.819	23.403	3.258
N16	-7.649	35.42	6.973
N18	7.649	35.42	-6.973
N20	.819	23.403	-3.258
N22	-10.891	17.677	18.577

Overall

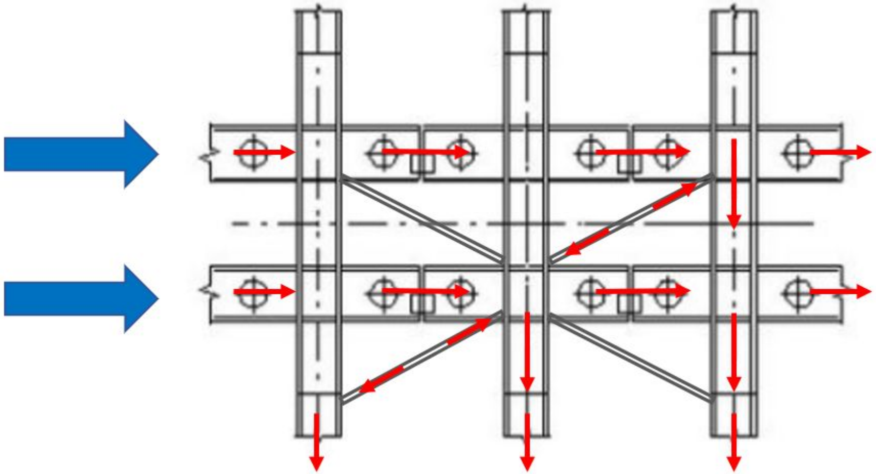




Lateral Loads



Frame Action



Truss Belt (Double Storey X-bracing)

Frame Action

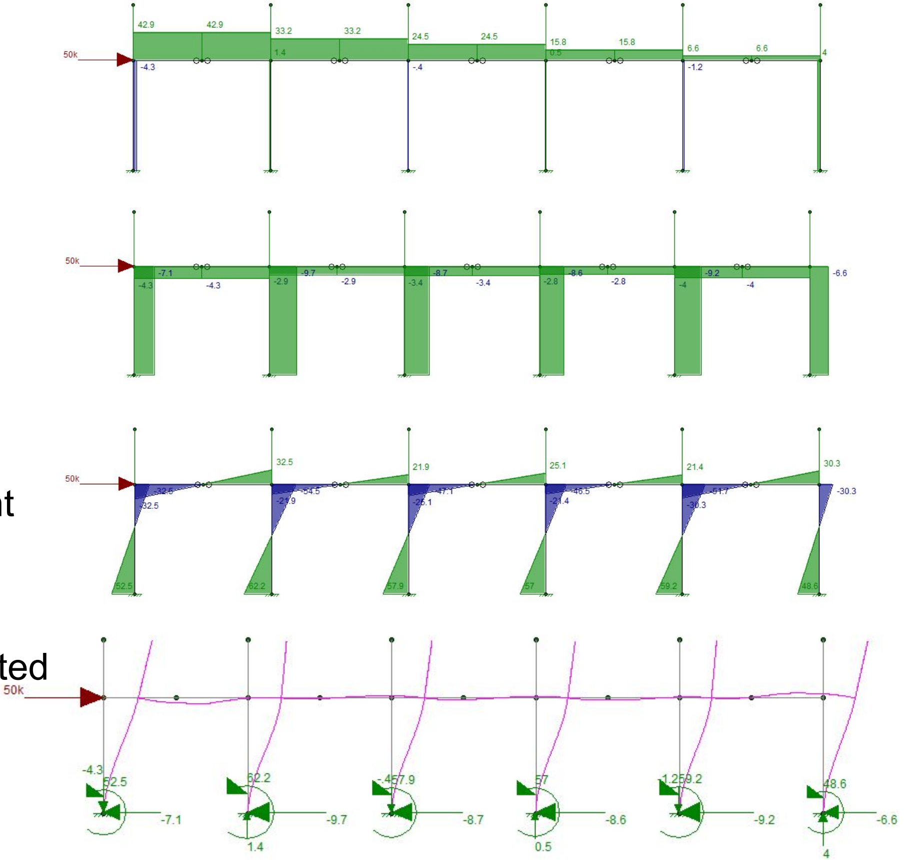
Truss Belt

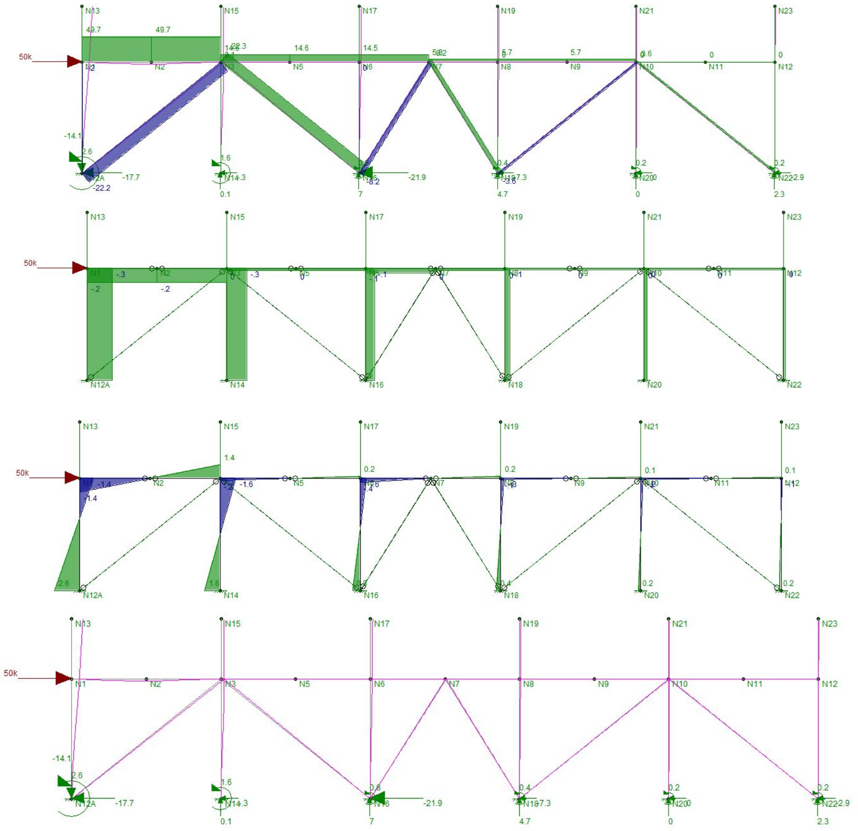
Axial

Shear

Moment

Deflected Shape





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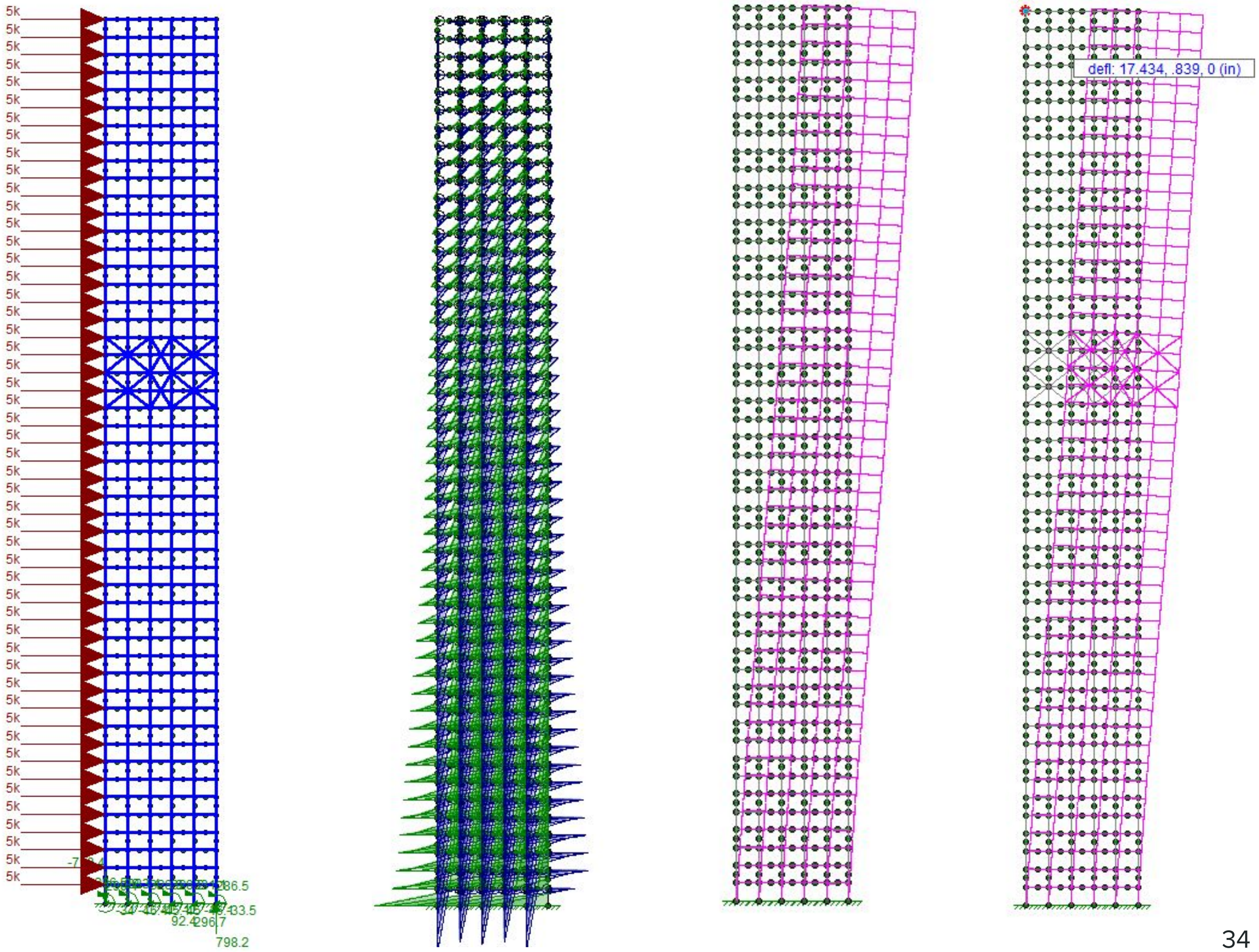
Single Tube (FL 1-50)



Challenges Faced

- Transportation
- Drastic temperature changes
- Heavy loads due to service floors
- Non-fatal and fatal accidents
- Leans 6 inches

In Conclusion...

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