Science, Engineering, and Speculation: The Collapse of the World Trade Center

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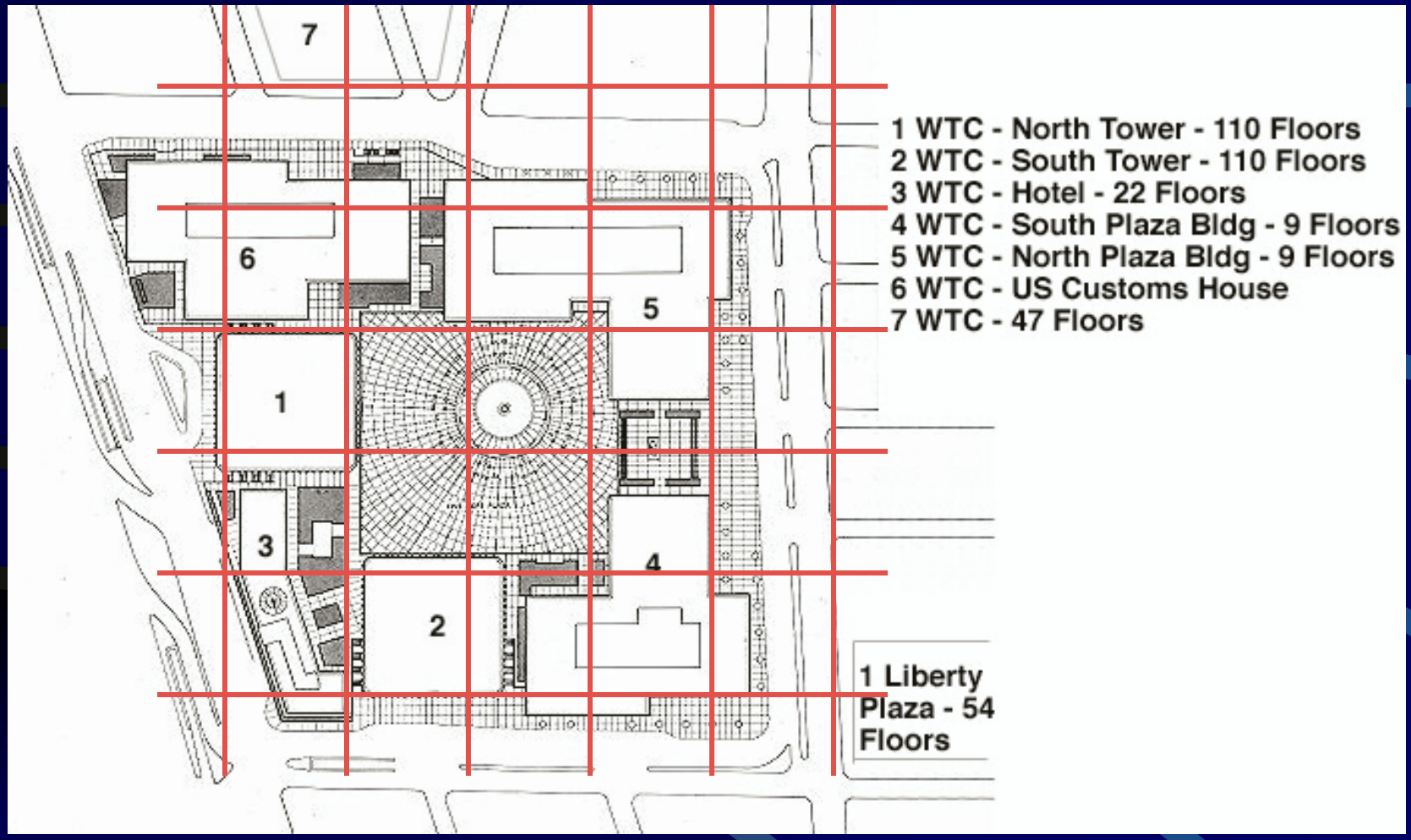
Common Questions and Reports

- Why didn t the Towers topple at impact?
- "The tower...could remain standing if hit by a 707"
  Les Robertson, WTC Structural Engineer (Chicago Tribune)
- "24,000 gallons of aviation fluid melted the steel."
  Hyman Brown, WTC Construction Manager (BBC Americas)
- Why did the buildings fall straight down?
- Were the Towers defectively designed?
- How should engineering design change?

WTC Facts

- Ground Breaking: August 5, 1966
- Opened: April 4, 1973
- Architect: Minoru Yamasaki
- Engineer: John Skilling
- Owners: Port Authority of New York & New Jersey
- 7 Buildings, 10 Million Square Feet

WTC Plan

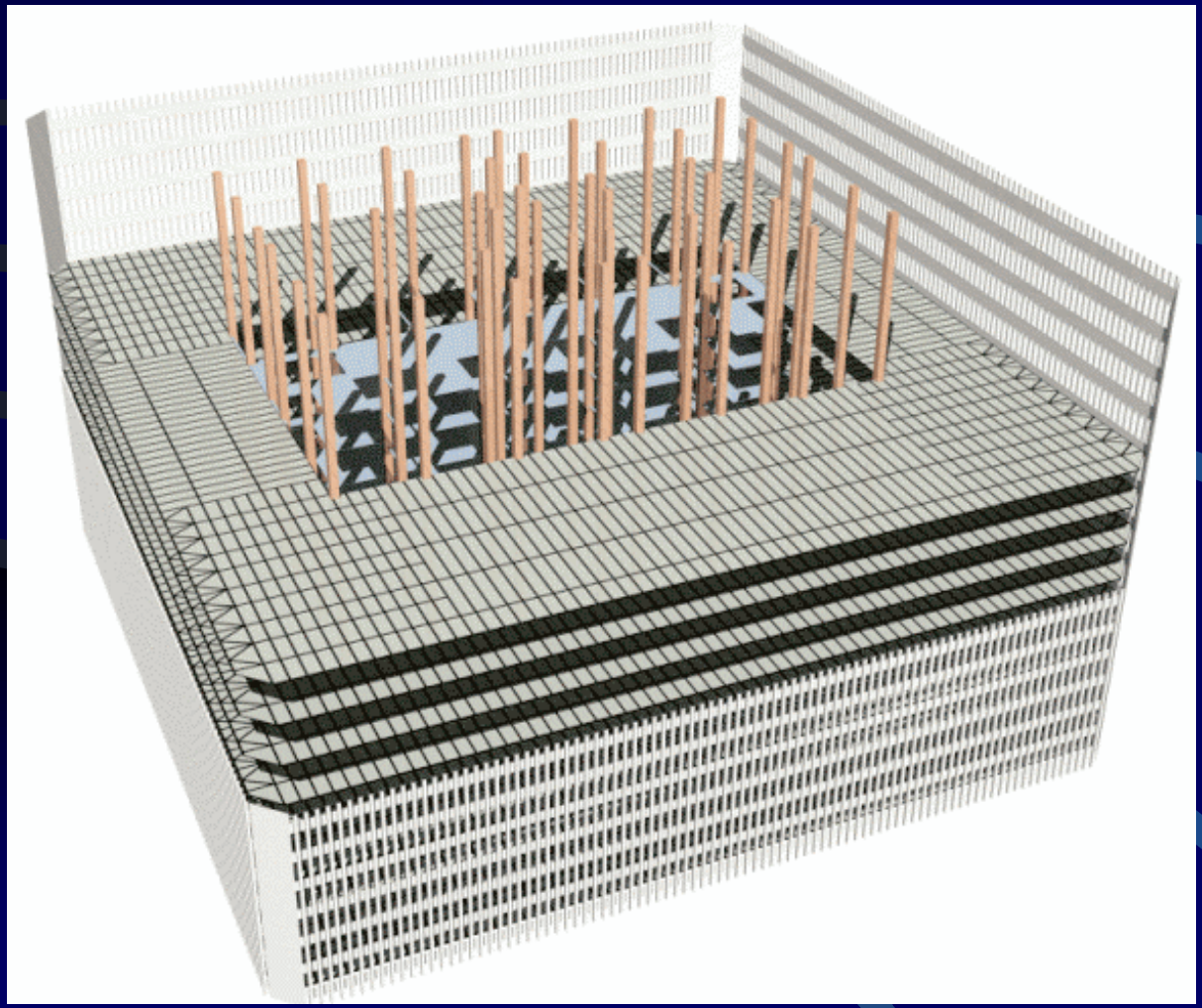

7
6
5
1
3
4
2
1 WTC - North Tower - 110 Floors
2 WTC - South Tower - 110 Floors
3 WTC - Hotel - 22 Floors
4 WTC - South Plaza Bldg - 9 Floors
5 WTC - North Plaza Bldg - 9 Floors
6 WTC - US Customs House
7 WTC - 47 Floors
1 Liberty Plaza - 54 Floors

Tower Facts

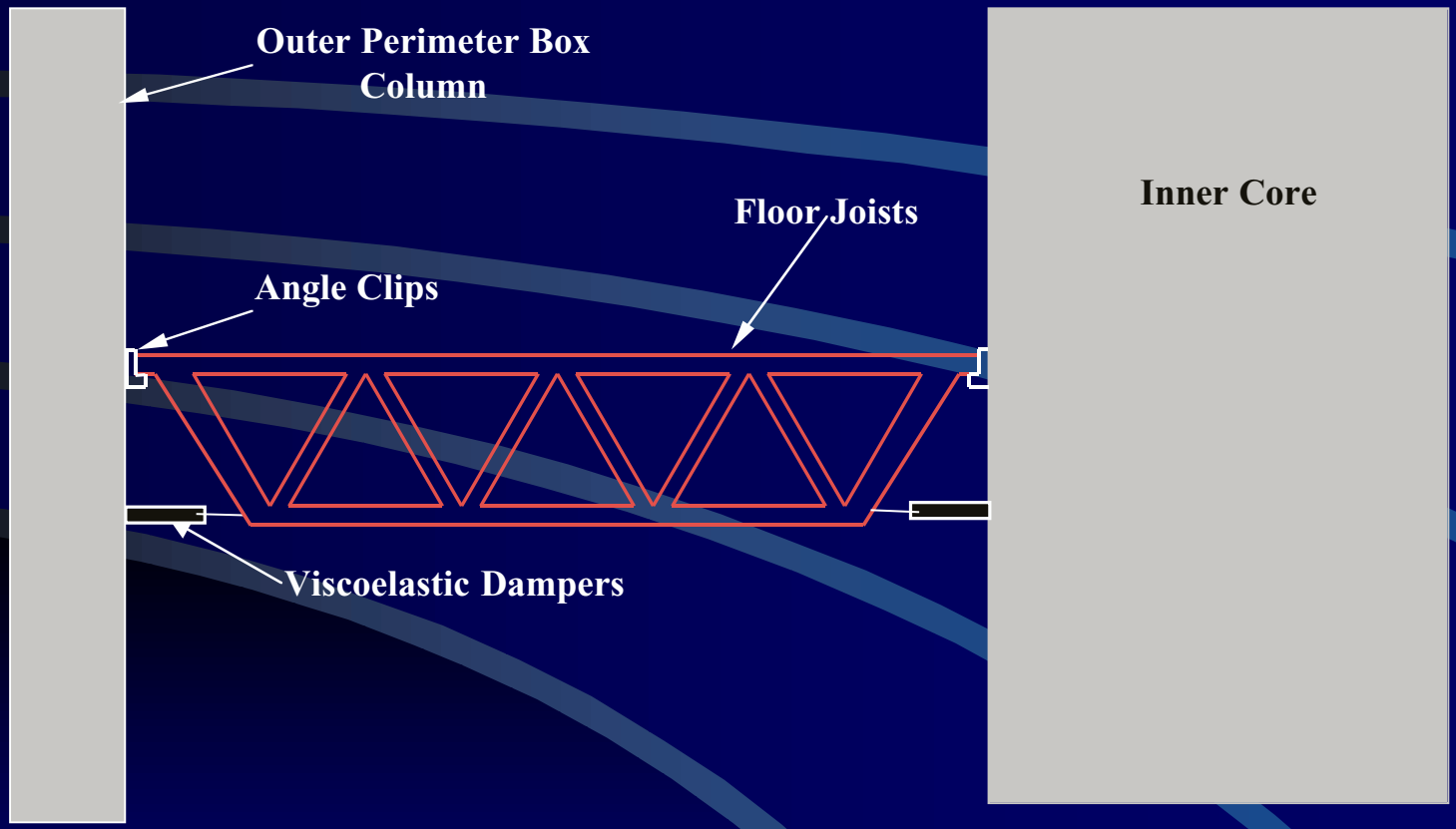
- Cost: ~$1 Billion each
- 110 Stories
- 1,362-1,368 ft (411 m) tall, ~70 ft (21 m) below grade
- 208 ft (63.5 m) on each side
- 90 ft x 130 ft (27 m x 40 m) core for ducting & elevators
- ~500,000 t each

Lightweight Perimeter Tube Design

One of the most redundant and one of the most resilient skyscrapers



Floor Joist Schematic



Eggcrate Construction

- Inner core carried gravity load- 500,000 t (10^9 lbs)
  —44 heavy box section steel columns

- Outer core carried wind load- 11,000,000 lbf (4.9×10^7 N)
  —59 14 in (36 cm) box section columns on each face, on 39 in (99 cm) centers

- 5/3 safety factor...less than 1/3 design load on outside columns on low wind day

On a low wind day, outer columns must lose 80% of strength to exceed design

September 11 Impacts

- 8:45 am: North Tower hit by American Flight 11, north face 96th floor.

- 9:03 am: South Tower hit by United Flight 175, south face, 80th floor.

Enormous Impact Energy

- Kinetic energy of 767 (worst case):

  350 mph (156 m/s), 350,000 lbs (150,000 kg)

  $K_i = 1.35 \times 10^9$ ft-lb (1.825×10^9 J)

- Very concentrated impact area-forces absorbed by bending, tearing, distortion of steel and concrete

- Perimeter tube design redistributed loads to nearby columns

Tower design dissipated impact energy

Towers Don t Topple

1. 1.35 billion ft-lb like bullet hitting tree
   - Concentrated energy penetrated instead of pushing

2. Inertia: Each Tower had over 2500 times more mass than aircraft.

3. *Fire was clearly principle cause of collapse*

Boeing Aircraft

Boeing 707-320B

Length	152 ft 11 in (46.6 m)
Wingspan	145 ft 9 in (44.42 m)
Gross Weight	336,000 lbs (152,400 kg)
Fuel Capacity	>23,000 gallons (> 87,000 l)

Boeing 767-200ER

Length	159 ft 1 in (48.5 m)
Wingspan	156 ft 1 in (47.6 m)
Gross Weight	395,000 lbs (179,170 kg)
Fuel Capacity	23,980 gallons (90,770 l)

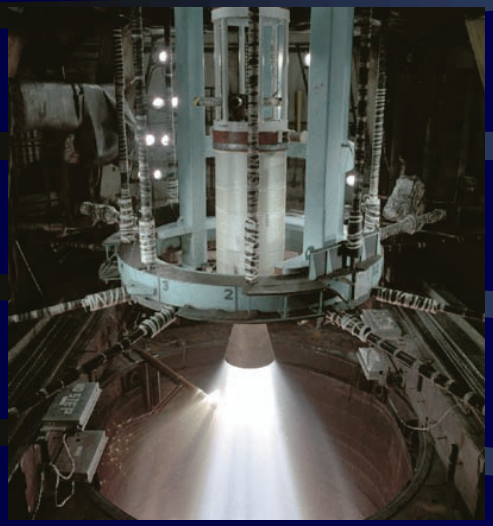
Similar sized aircraft-Design for 707 impact also handled 767 impact

Heat vs. Temp

- Heat: Energy, measured in calories or Joules. Extensive property related to temperature.
- Temperature: Measure of vibrational and rotational energy stored in atoms, measured in degrees. Intensive property.
- Temperature and heat related by density and heat capacity.

Small stove burner can t heat a large pot

Understanding Flames



Jet Burner:	Premixed Flame:	Diffuse Flame:
2000W/cm^2	1000 W/cm^2	0.1-10 W/cm^2
Stoichiometric burn temperature	Stoichiometric burn temperature	Lower burn temperature; non- stoichiometric

Tower Fire was Diffuse Flame

- Stoichiometric hydrocarbon burn~ 5480° F (~3027° C)
- Maximum temperature in air: 1520° F (~825° C)
- WTC fire was fuel rich could not have been 1520° F

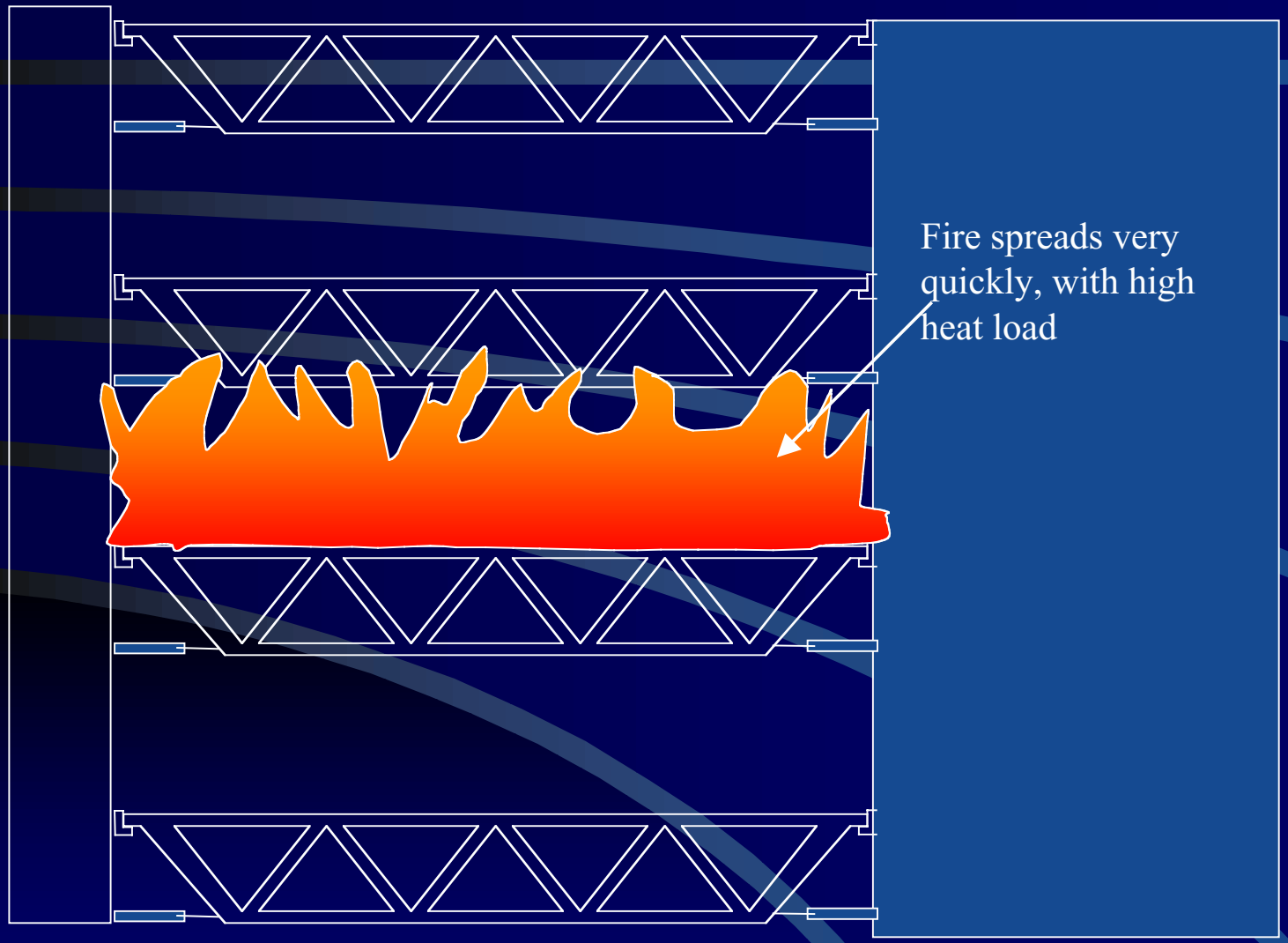
Temperature in Tower fires about the same as typical office fires

Steel Weakened and Distorted

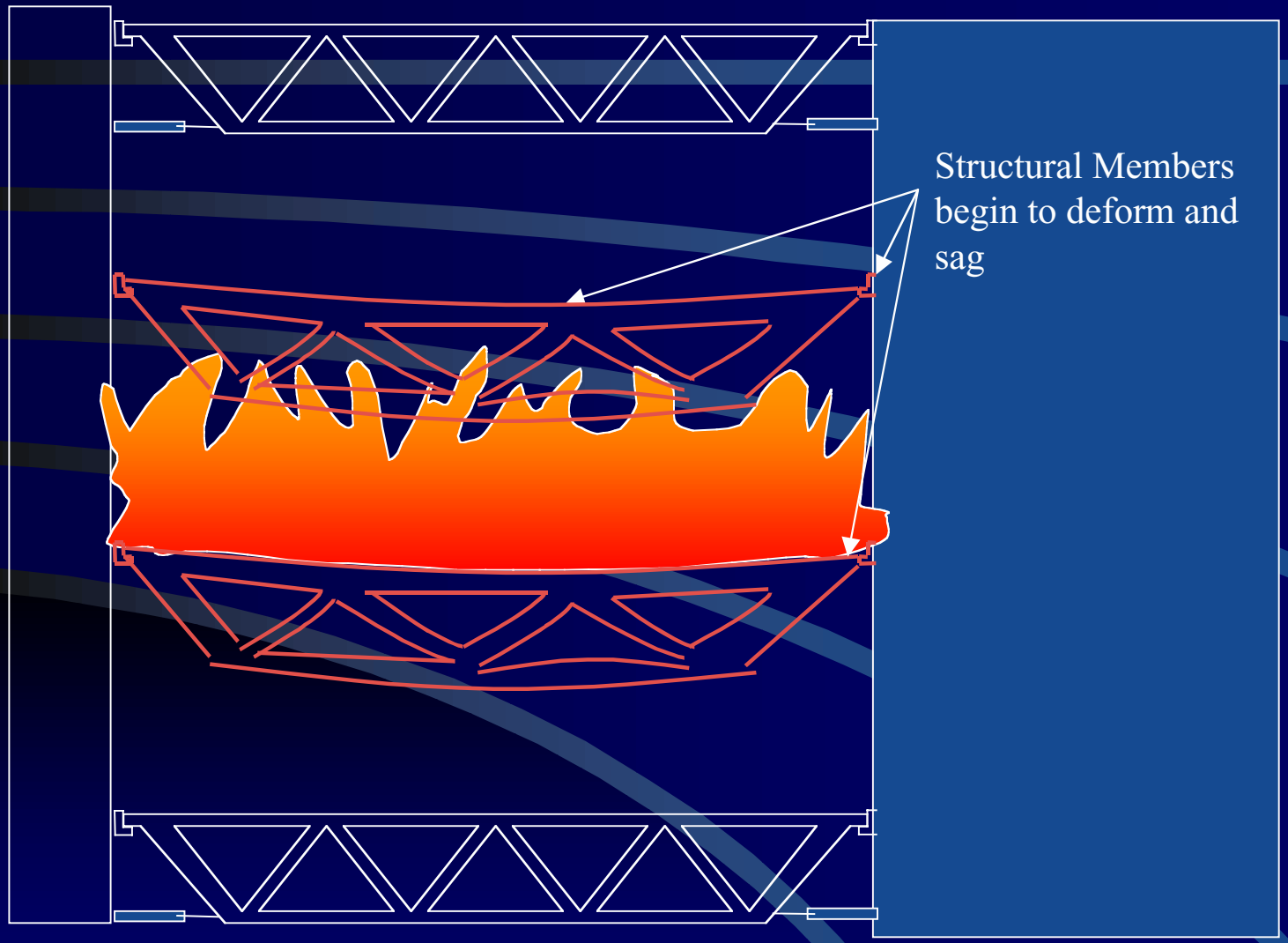
- T_m of Steel: ~2750° F (1500° C)
  - —Steel could not have melted, but was weakened
  - —30%-40% of RT strength at 1500° F
- Thermal gradients on outside columns create yield level stresses
  - —Cool outside, hot inside induced thermal expansion mismatch between inner and outer faces
- Non-uniform heating on long floor joists

Combination of softening, loss of structural integrity, distortion induced buckling

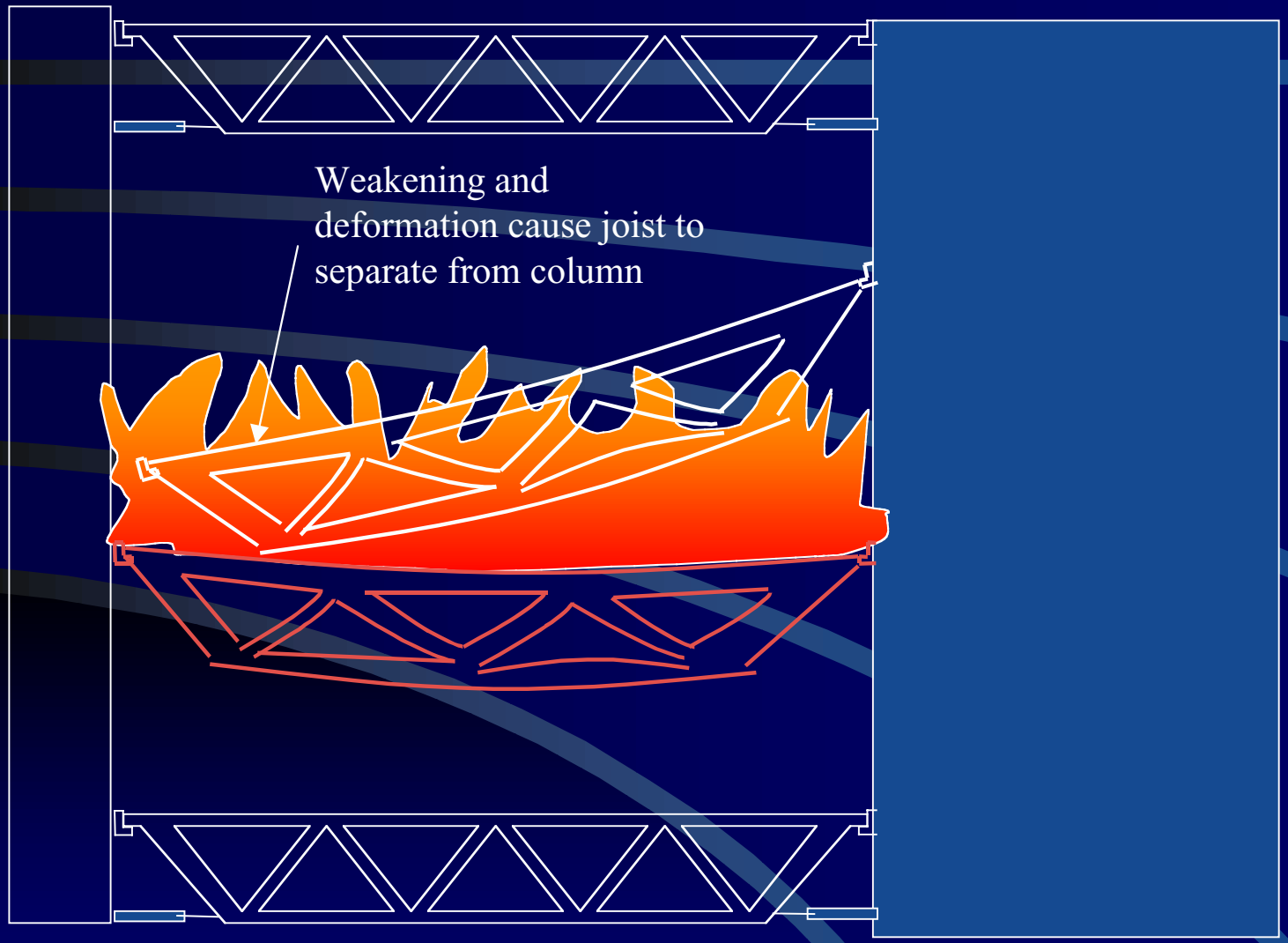
Structural Failure (1)



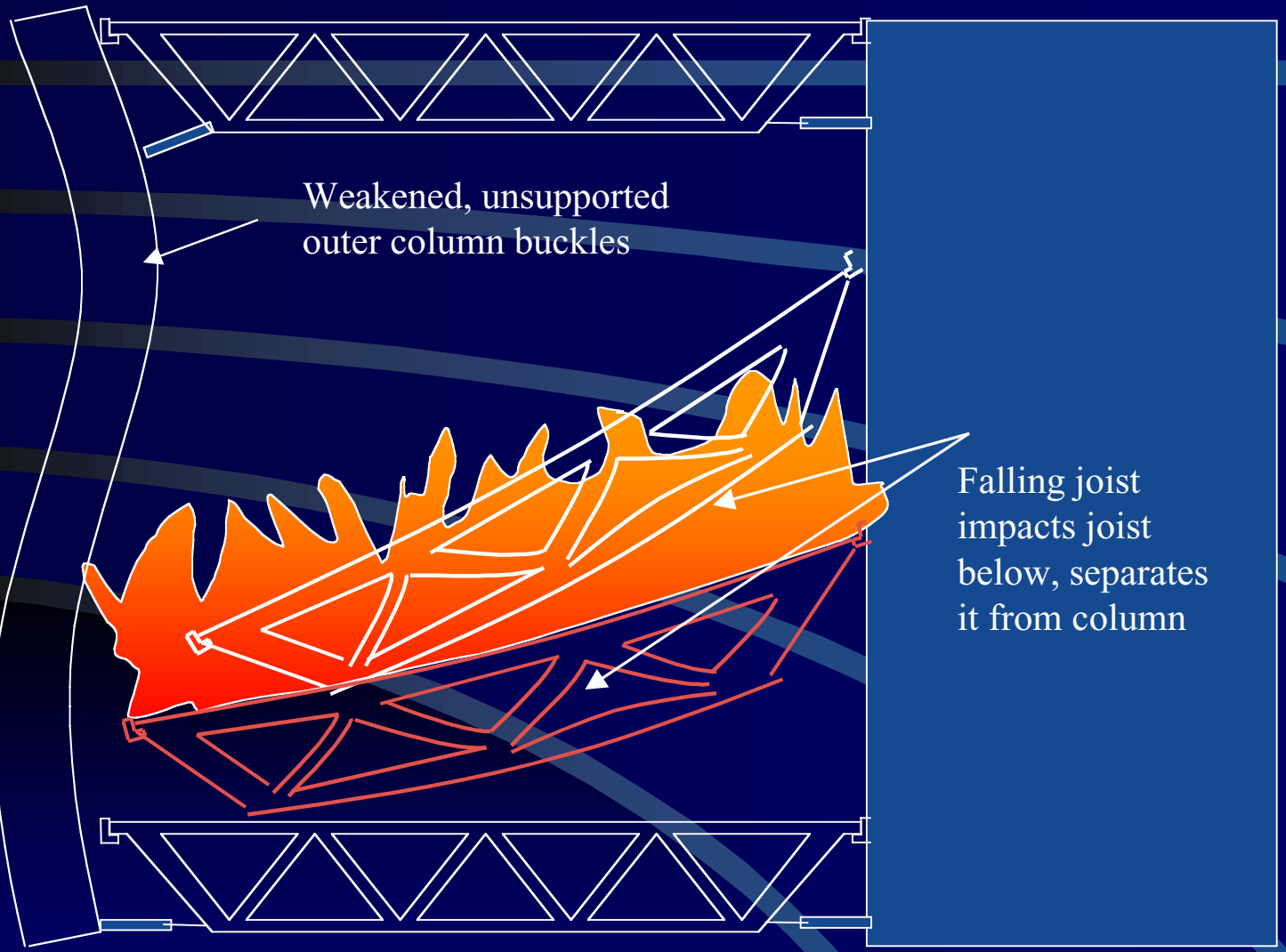
Structural Failure (2)



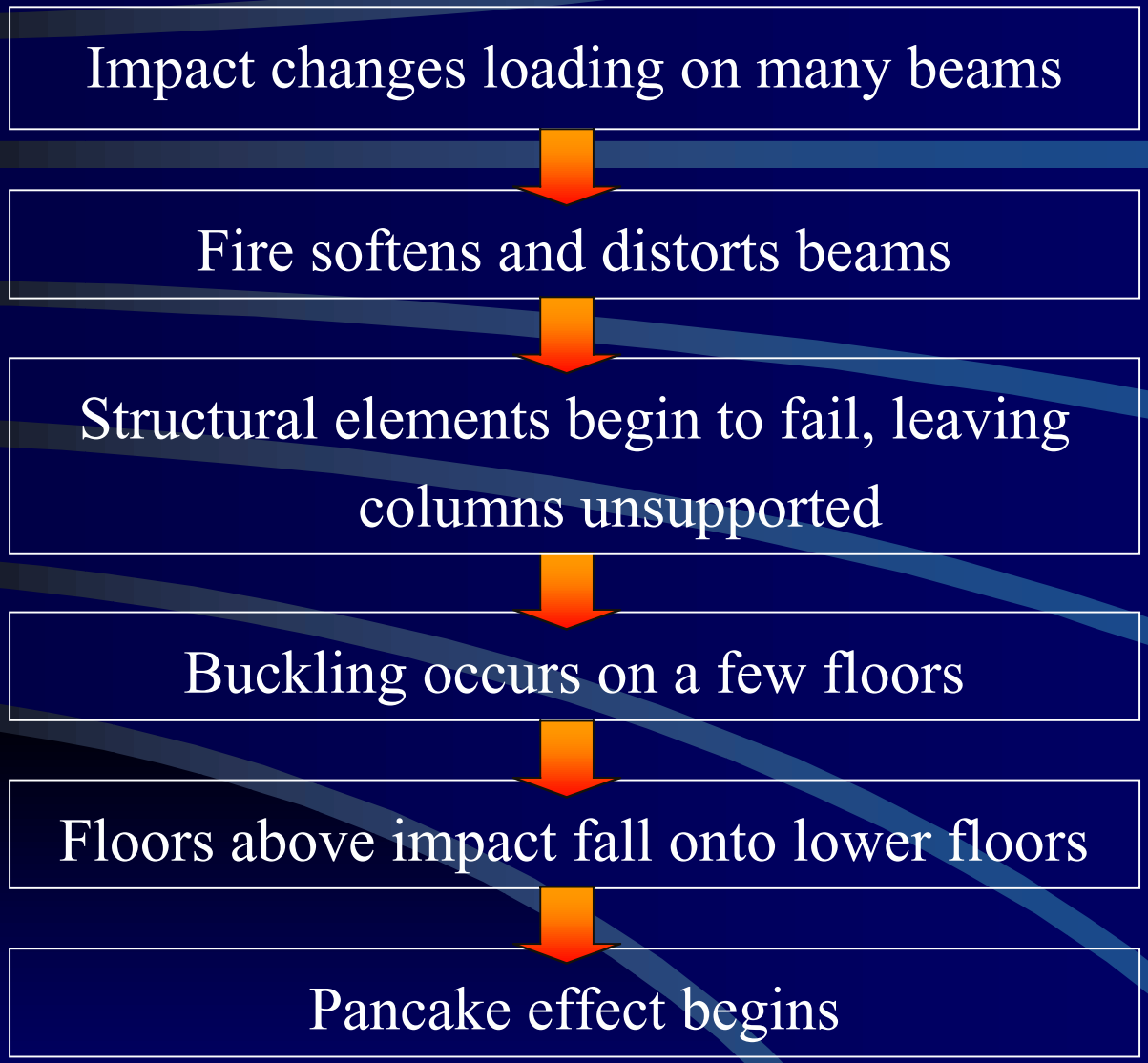
Structural Failure (3)



Structural Failure (4)



Structural Failure Sequence



Structure Couldn' t Handle Falling Load

- Floors rated for ~1300 t
- At least 15 floors above impact site >45,000t
- Bazant and Zhou (Northwestern University) estimate overload ratio of 64.5 at time of impact!

Buildings fell in approximately 10 seconds - - very close to free fall.

Towers Fell Straight Down

- Bending strain severed backside columns
- Tube design: 90% air
- Lower floors could not support falling load
- Cg would have to sway over 100 ft (30 m) to topple!

Towers Were Not Defectively Designed

Extraordinary Circumstances:

- Heavy structural damage
- Fire insulation ripped away in impact
- Very high heat load
- Very fast and thorough dispersion of fire

Towers Survived:

- South Tower: 47 minutes
- North Tower: 1 hour 44 minutes

WTC endured impact and inferno long enough for most people to escape

The buildings displayed a tremendous capacity to stand there despite the damage.

-Robert McNamara *Scientific American*,
October 9, 2001

WTC Questions

1. Why didn' t the Towers topple at impact?
2. Could the Towers have handled a 707?
3. Did the steel melt?
4. What caused the final failure?
5. Why did the towers fall straight down?
6. Were the towers defectively designed?
7. How should engineering design change?

Responsibility of Engineers: Safety

- Focus on Survivability:
  - Better evacuation plans and systems
  - Better communications systems
  - Reasonable structural fortification
  - Improved fire insulation materials

Safety does not mean invincibility

Responsibility of Engineers: Redundancy

- In Buildings:
  - Redundant fire and communications systems
- Contingency designs for any public artery:
  - Transportation: subways, bridges
  - Necessities: food supplies, power grid, gas pipelines

Redundancy undermines terrorism

Responsibility of Engineers: Training & Leadership

- Engineers understand failure modes, must train:
  - Rescue workers
  - Code writers
  - Law makers
  - Maintenance groups
- Engineering guidance and leadership is critical to crisis management

Better training prevents triage in the courtyard

Responsibility of Engineers: Thoughtful Communication

- Public needs and deserves answers
- Complete analysis not always needed
- Breadth of understanding required
- Speaking a "new language"

Analysis eliminates myths, strengthens public confidence

Moving Forward

Greatness is found when American character and American courage can overcome America s challenges

-President Bush