

THE 35TH ANNUAL
AGC NYS
 INDUSTRY CONFERENCE



How The Towers Fell – Part 1/3
 How the WTC Twin Towers Were Constructed &
 Lessons Learned From the 1993 Bombing

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 HNTB Corporation

Wednesday December 8, 2021, 12:45 PM Workshop
 Saratoga Hilton Hotel
 534 Broadway, Saratoga Springs, NY 12866



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Agenda (Learning Points)

- Construction of WTC Complex and PATH Station: Why and How?
- Construction Details that Played a Role in Building Performance During Two Attacks
- Evacuation of the Buildings and Emergency Response
- The 1993 Terrorist Bombing: How it was Executed
- Description of the Damage
- Recovery Project and Role of Engineers: Damage Assessment, Recovery Operations and Reconstruction
- Lessons Learned From Evacuation and Emergency Response

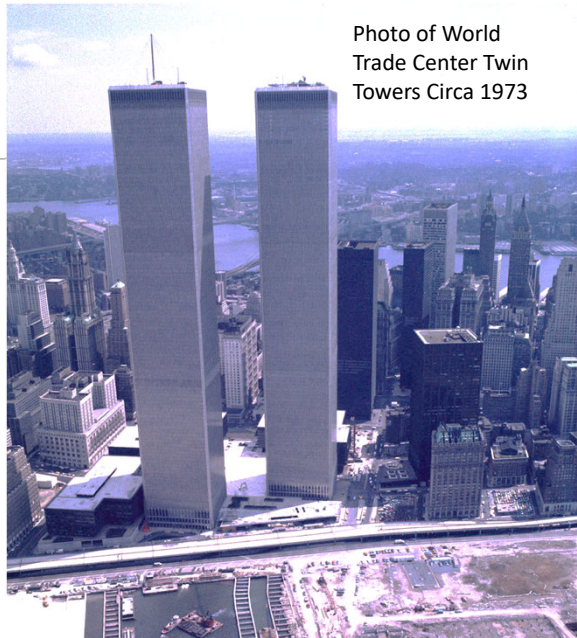


Photo of World Trade Center Twin Towers Circa 1973

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Acknowledgements

1. The Port Authority of NY & NJ was the owner, planner, financier, design and construction manager, operator and maintainer of the World Trade Center and PATH Station for the time period represented in part 1 of 3. Ray M. Monti was the Project Manager for the WTC project, won the 1971 ENR Award of Excellence, and became the PANYNJ Chief Engineer.
2. Others who played a key role in building the WTC Complex:
 - a. Architects: Minoru Yamasaki & Associates and Emory Roth & Sons
 - b. Engineers: John Skilling & Les Robertson & PANYNJ Geotechnical: George Tamaro
 - c. Contractor: Tishman Construction Company
3. Reconstruction of the WTC complex after the 1993 Bombing
 - a. Port Authority of NY & NJ was the owner, planner, design and construction manager, operator and maintainer
 - b. Consulting Engineer: LERA
 - c. Contractors: Karl Koch & Slattery

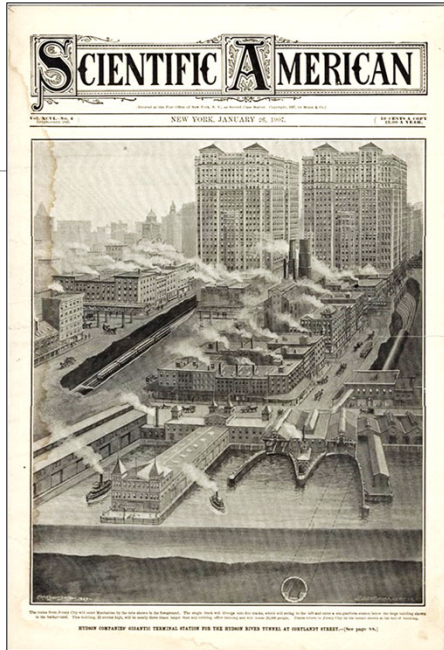
Note: Sadly, Les Robertson passed away in February just before his 93rd birthday.

Note: The technical information and professional opinions presented represent the recollections of the author supported by information collected from published references and are provided in the interest of sharing this information with the audience to make a positive contribution to the public's understanding of events.

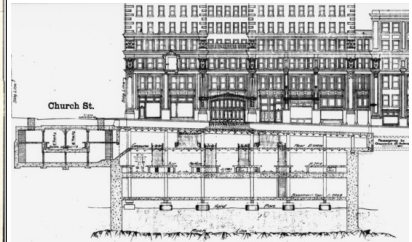
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Hudson and Manhattan (H&M) Railroad

- Cover of Scientific American January 26, 1907
- Located on Church Street H&M Terminal was world's largest office building
- Hudson River in foreground, cutaway sections through the inbound and outbound "tubes"
- H&M Terminal station platforms below the office building



H&M Terminal Circa 1910 Looking South (Postcard: Museum of City of NY)



Cross Section of H&M Terminal Station Platforms Below Building Looking South

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Construction of the Hudson and Manhattan (H&M) Railroad Terminal

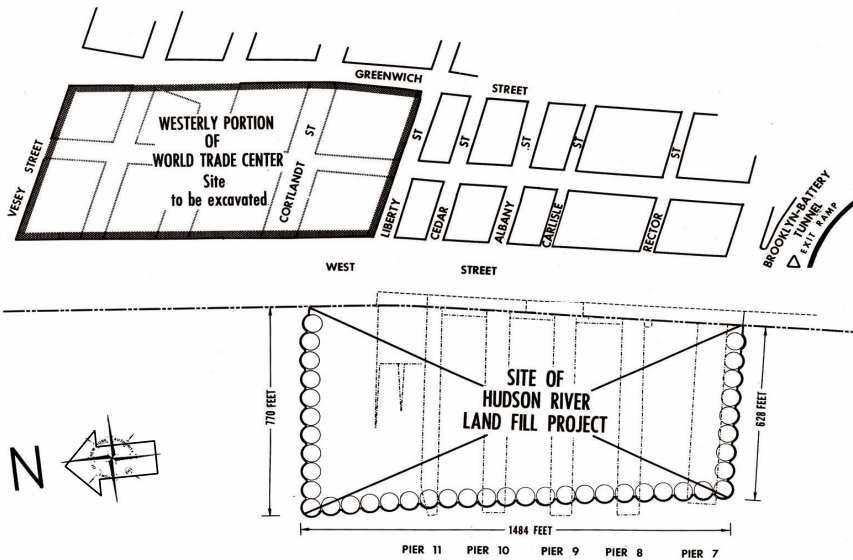
- Photo shows 1906 top-down construction to bedrock of the H&M building basement and foundations
- Space housed the Cortlandt St. Station of the H&M Terminal
- This space was to later become WTC basement truck loading dock
- The Elevated 6th Avenue Subway on Church Street is in the background
- Elevated line was to be taken down after a new underground subway line (now called N & R line) was constructed below church street & directly connected to the new H&M Terminal Station



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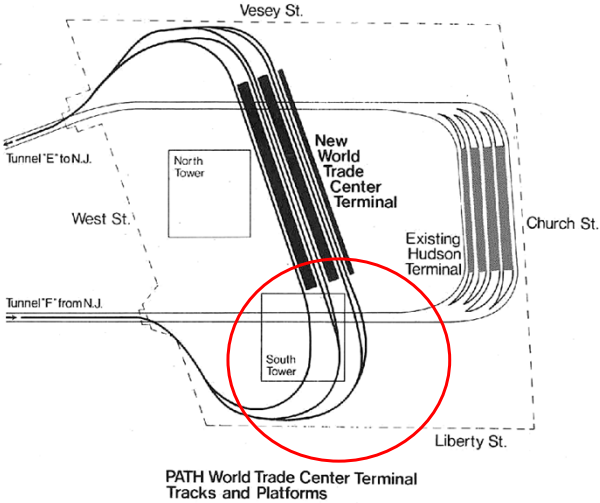
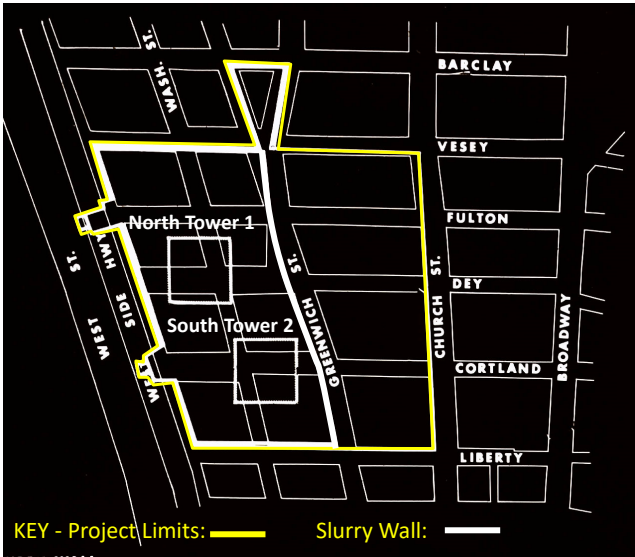
Construction of WTC Complex and PATH Station

- Deep Excavation of the Western half of site
- 1 & 9 Subway underground below Greenwich Street on East
- Large volume of excavated soil to be placed in new land fill
- **Must keep existing H&M Trains (now called PATH) running until new station opens under the new twin towers**



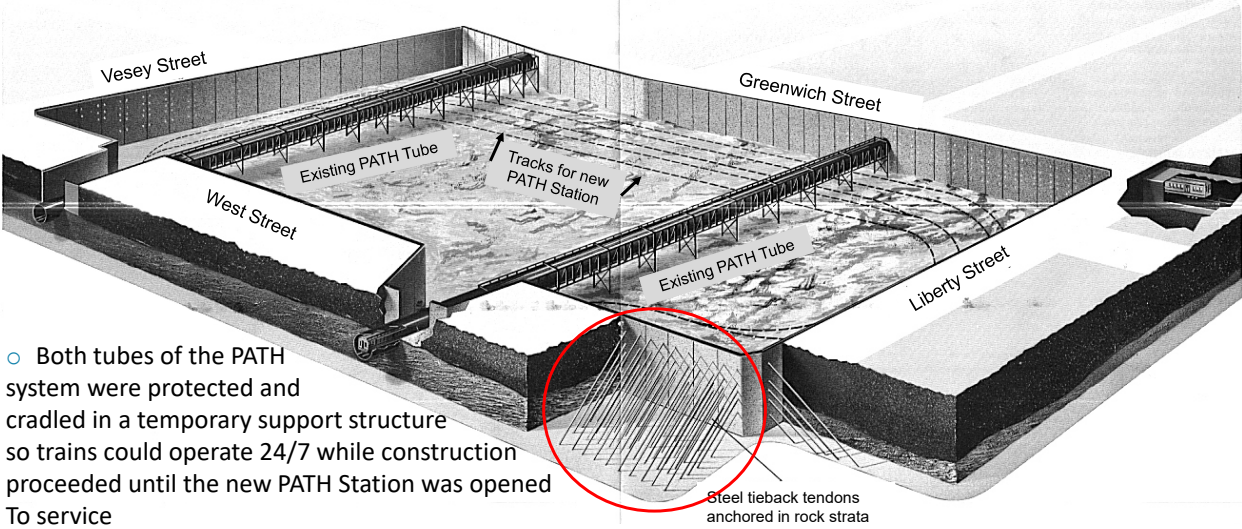
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Construction of WTC Complex and PATH Station – Deep Foundation Walls



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Construction of WTC Complex and PATH Station – Deep Foundation Walls

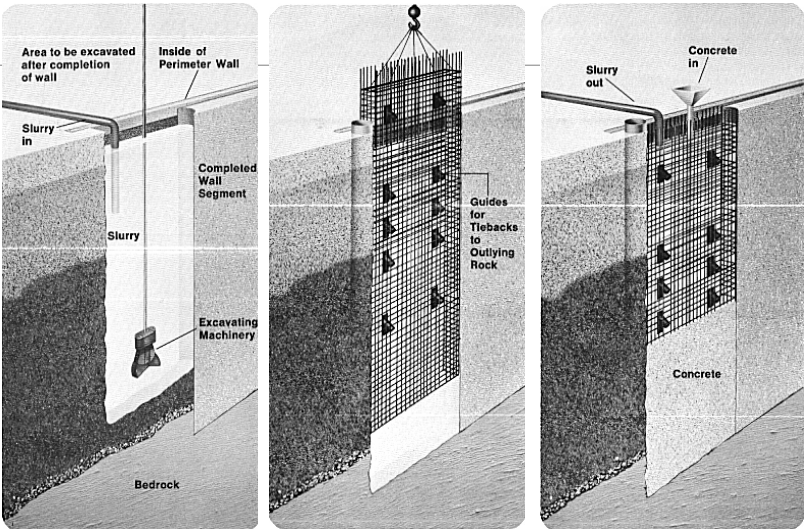


- Both tubes of the PATH system were protected and cradled in a temporary support structure so trains could operate 24/7 while construction proceeded until the new PATH Station was opened To service

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Construction of WTC Complex and PATH Station – Deep Foundation Walls

- The **slurry wall method** of retaining wall construction was used in the United States for the first time
- Dense Bentonite slurry is pumped into the excavation as soil is removed to exert fluid pressure to hold back the earth
- A steel rebar cage is lowered into the excavated hole
- Concrete is pumped into the excavated hole to displace the slurry which is pumped out
- As the inside of the new concrete retaining wall is excavated, soil anchors are installed to hold back the earth pressure



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Construction of WTC Complex and PATH Station – Deep Foundation Walls



- Circular coffer dams were used to create a bulkhead to retain the large quantity of excavated soil in the land fill
- Crane lifting a rebar cage that was prefabricated to lower it into an excavation stabilized by Bentonite slurry

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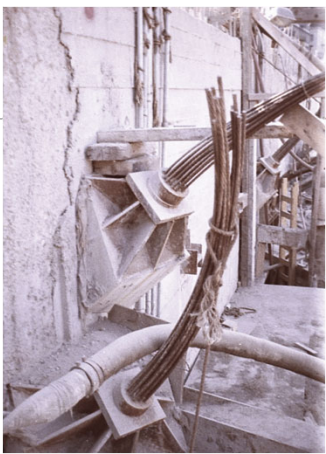
Construction of WTC Complex and PATH Station – Deep Foundation Walls



- The foundations for the 1 WTC Tower are shown under construction. They consisted of structural steel grillages founded directly on bedrock. The NJ-bound PATH line is in the background.
- View of the retaining wall at Greenwich St. which supported the excavation to a depth of six stories below street level. Here the old PATH line crosses under the 1 & 9 Subway line. Both lines remained in operation.

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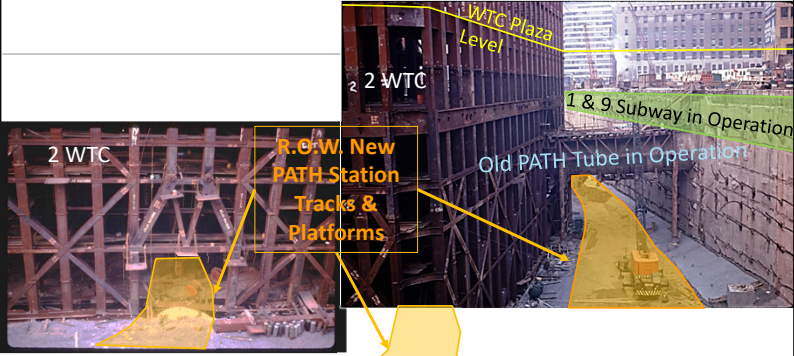
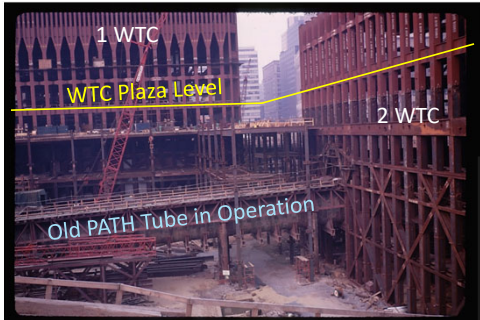
Construction of WTC Complex and PATH Station – Deep Foundation Walls



- Tiebacks (left and center) consisting of high strength steel cable strands were jacked and then anchored with wedges to provide the prestressed lateral force to hold back the earth after wall was excavated to full depth.
- The tiebacks extended beneath adjacent properties or city streets and were considered temporary. Upon completion of the interior diaphragm slabs of the WTC basement which would be permanently relied upon to brace the walls they were decommissioned by removing the anchor heads.
- Right, a construction access ramp from West Street to provide access for heavy equipment as the excavation gets deeper.

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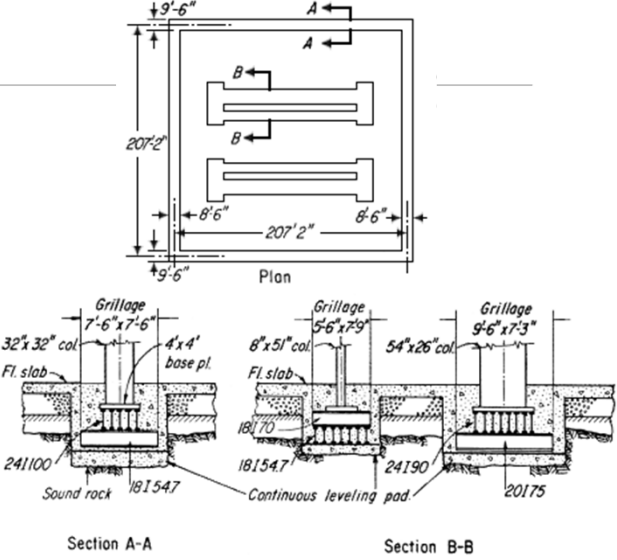
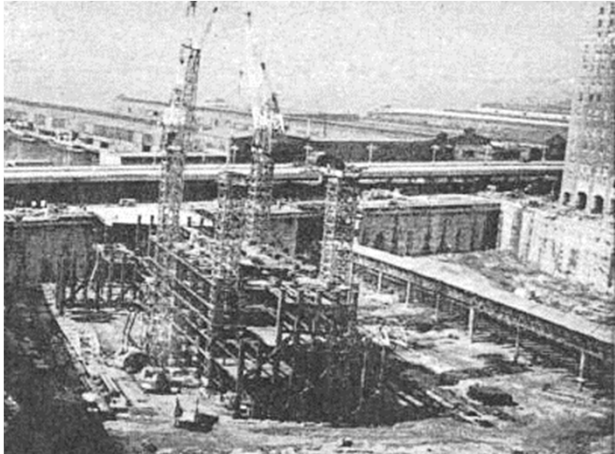
Construction of WTC Complex and PATH Station – Deep Foundation Walls



- o Photo above shows logistics and staging required to maintain the old existing PATH/H&M operations going during construction of the new WTC Towers 1 and 2. The existing train tunnel passed through Tower 2 on right at the B-5 & B-4 basement level.
- o Above center we see the new PATH station track alignment which passes through and under Tower 2 at the B-6 basement level in center (above) and at the tower corner (right).
- o The right side also shows logistics and staging to work around both the existing PATH and 1 & 9 Subway operations behind the slurry wall during construction and below the new WTC Plaza level

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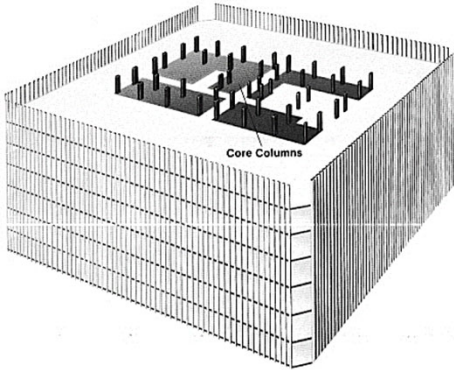
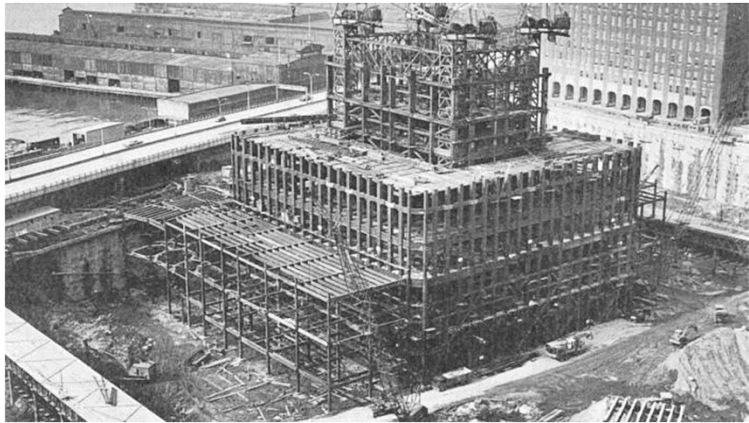
Construction of WTC Complex and PATH Station – Towers & Plaza



- o Above: Tower 1 Steel Erection Begins starting with the core which supports the Kangaroo Cranes that will advance by jacking upward to erect all steel and prefabricated floor systems & exterior cladding
- o Right: Foundation Plan, Core and Perimeter Column Steel Grillages

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Construction of WTC Complex and PATH Station – Towers & Plaza

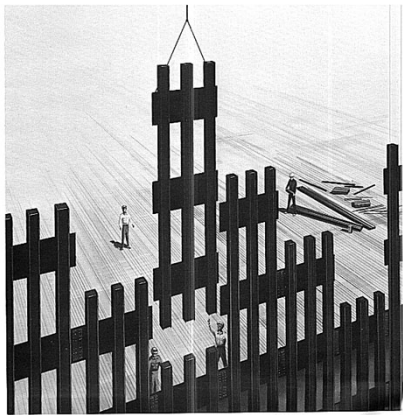


- Tower 1 erection of core followed by erection of steel perimeter “tree” columns and prefabricated deck elements made from long span joists followed by erection of steel supporting the plaza up to the concourse level.

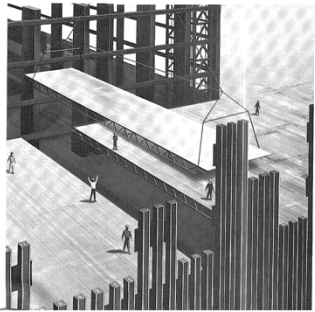
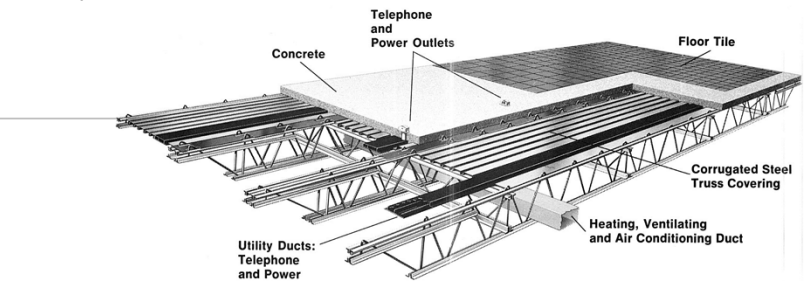
- The Wall and Core: Typical tower floor provided almost an acre of unobstructed office space on each floor with the outer **load bearing wall forming a giant tube structure** that provided lateral stability and stiffness to resist wind loads with up to a 10,000-year return period.

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Construction of WTC Complex and PATH Station – Towers & Plaza



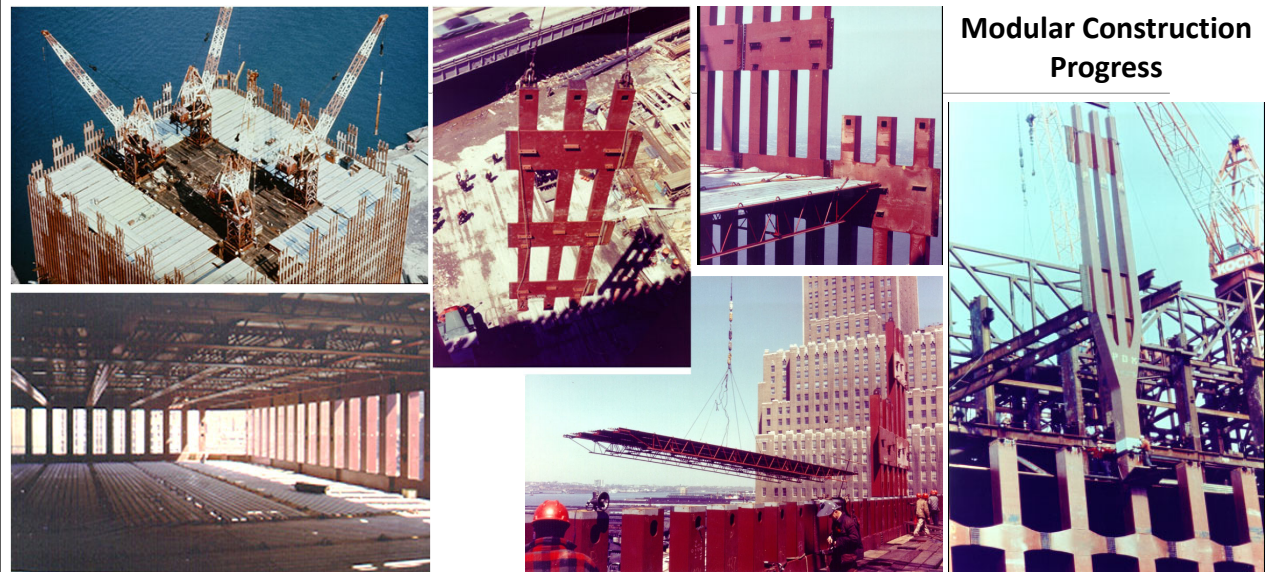
- Above: The tower perimeter load bearing wall was erected with prefabricated panels with vertical columns shop welded to horizontal spandrels. The unit shown weighs 22 tons and is 36 feet tall and 10 feet wide.



- Above: The floor panels are prefabricated with supporting long span steel truss joists and corrugated steel deck. Utility chases and air conditioning ducts are within the 32-inch deep ceiling space. The concrete slab, floor tile, ceiling tracks and ceiling tile are installed on site.
- Left: Floor Framing: Typical prefabricated floor panel is 60 ft. by 13 ft. and is lowered into place after the load bearing wall is constructed behind the core columns.

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Construction of WTC Complex and PATH Station – Towers and Plaza



Modular Construction Progress

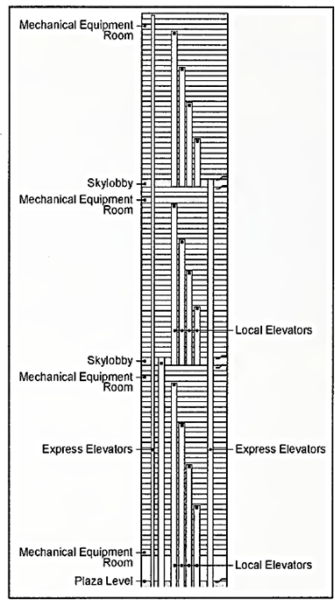
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Construction of WTC Complex and PATH Station – Towers and Plaza



Construction Progress Photos

- Upper left: Note the tower cores oriented at 90 degrees to each other to avoid sympathetic behavior with wind load vortex shedding effects
- Right: The WTC's **Innovative Elevator System** optimized the use of the Core Space in the Towers and expedited elevator travel by utilizing both Express and Local Elevators. The 3 different banks of local elevators occupied the same vertical shaft space in the tower core.



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Assessment of Learning WTC Construction

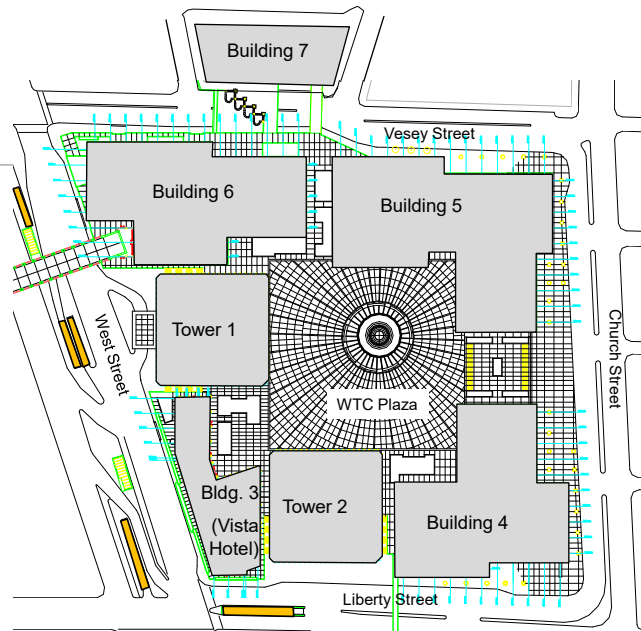
1. Name five innovative design or construction methods that were employed to build the World Trade Center complex?
 1. "Slurry method" for retaining wall construction
 2. "Kangaroo" cranes used to erect the towers
 3. Modular construction of floor panel and exterior wall panels
 4. Exterior load bearing wall acts as a giant structural tube to resist lateral loads
 5. Express and local elevators optimized vertical circulation in the towers
2. What was the biggest logistical challenge to building the World Trade Center Complex and new PATH Station?
 1. Maintaining PATH service for the duration of construction.

Maintaining PATH service for the duration of construction.

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1993 Bombing of WTC Complex, Emergency Response, Recovery and Reconstruction

- Evacuation of the Buildings and Emergency Response
- The February 26, 1993 Terrorist Bombing: How it was Executed
- Description of the Damage
- Recovery Project: Damage Assessment, Recovery Operations and Reconstruction
- Lessons Learned From Evacuation and Emergency Response and Improvements Made



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U.S. Fire Administration: The 1993 World Trade Center Bombing: Report and Analysis

- Largest incident ever handled in the City of New York Fire Department’s 128-year history (16-alarm fire)
- 6 deaths, 1,042 injured (including 88 firefighters, 35 police officers and 1 EMS worker)
- Largest building evacuation on record
- 50,000 people evacuated from WTC complex, 25,000 from the two towers
- 1,000 phone calls to FDNY from trapped victims
- 45% of on-duty staff at FDNY responded and maintained presence for 28 days (24/7 around the clock and provided 3 meals a day by the Port Authority of NY/NJ)

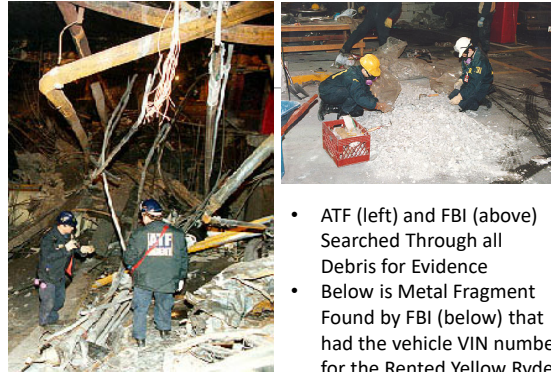
Source: U.S. Fire Administration: The 1993 World Trade Center Bombing: Report and Analysis: Report from Anthony L. Fusco, Chief of Dept., FDNY



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WTC Bombing: Search for Crime Scene Evidence Amidst Site Safety Concerns

- FBI and ATF (Bureau of Alcohol Tobacco, Firearms and Explosives) were immediately on site searching for crime scene evidence (ATF HQ next door at Post Office on Church St.)
- The Port Authority (Office of Emergency Management, Engineering Department, Risk Management and WTC Operations) also needed access to assess site safety and damage
- There was a concern for structural stability of the crime scene, the safety of investigators and the need for shoring to make it safe. Also concern that night of asbestos in air and phosgene gas from combustion of chiller freon that led to air sampling etc.
- The PATH Station below had minor damage but there was a concern that vibration from trains operations could cause further collapse
- Safety is a recurring issue for those investigating terrorist acts or industrial accidents that result in physical damage and potential structural instability

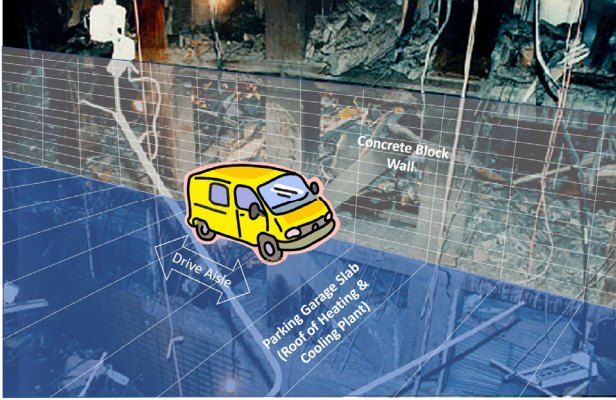


- ATF (left) and FBI (above) Searched Through all Debris for Evidence
- Below is Metal Fragment Found by FBI (below) that had the vehicle VIN number for the Rented Yellow Ryder Van

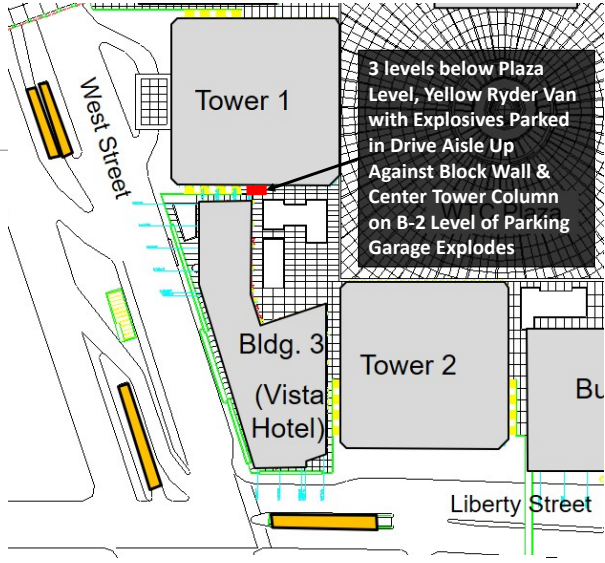


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Findings for 1993 Bombing of WTC Complex:
 On Friday, February 26, 1993, a violent explosion
 ripped through a parking garage in the sub-
 basement levels of New York's World Trade
 Center . In excess of 1,000 TNT equivalent.



B-2 Level Damaged Tower Column and Missing Bracing Member



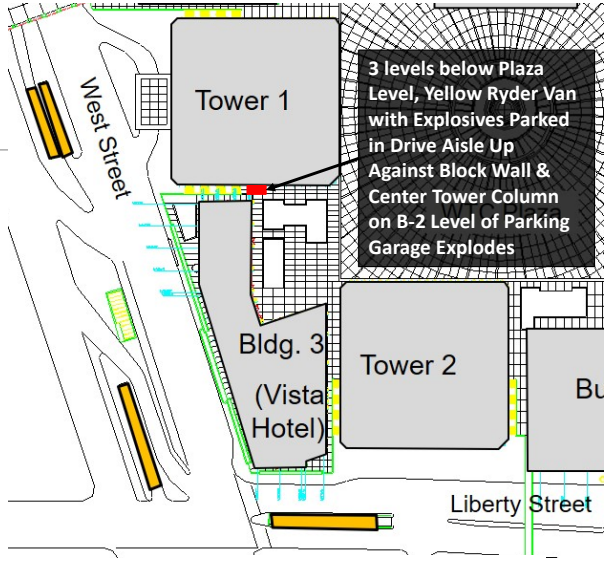
Partial Plan WTC Plaza Level

Source: World Trade Center Explosion & Fire, New York, NY February 26, 1993, NFPA Fire Investigations

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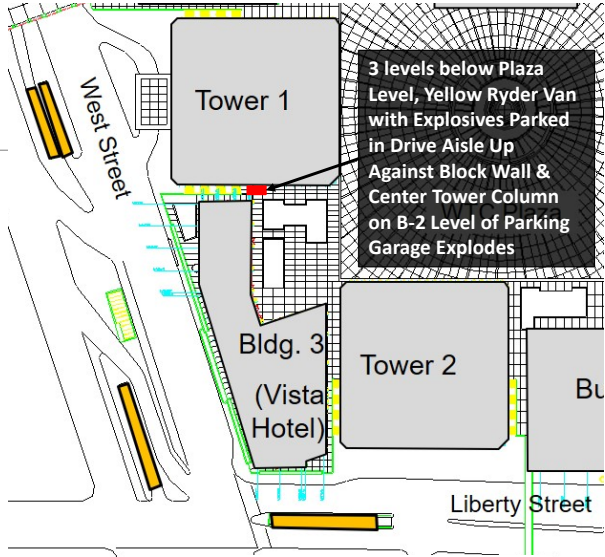


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 On Friday, February 26, 1993, a violent explosion ripped through a parking garage in the sub-basement levels of New York's World Trade Center. In excess of 1,000 TNT equivalent.

- Nitrourea was used as the bomb's base and cylinders of hydrogen were used to increase the magnitude of the explosion.
- Nitrourea, a white, crystalline powder, is a Class A explosive equivalent to TNT in force.
- Its caloric value (power as described by the number of joules of energy per kilogram of weight) is 34 percent greater than TNT's.
- Source: Frank L. Fire, instructor of hazardous- materials chemistry at the University of Akron.

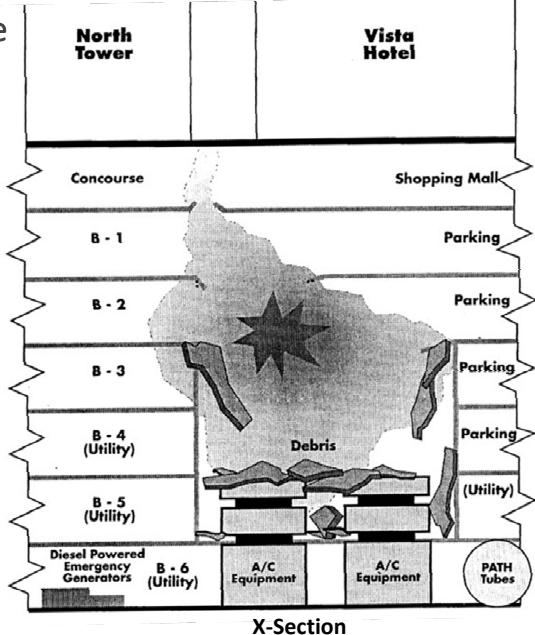
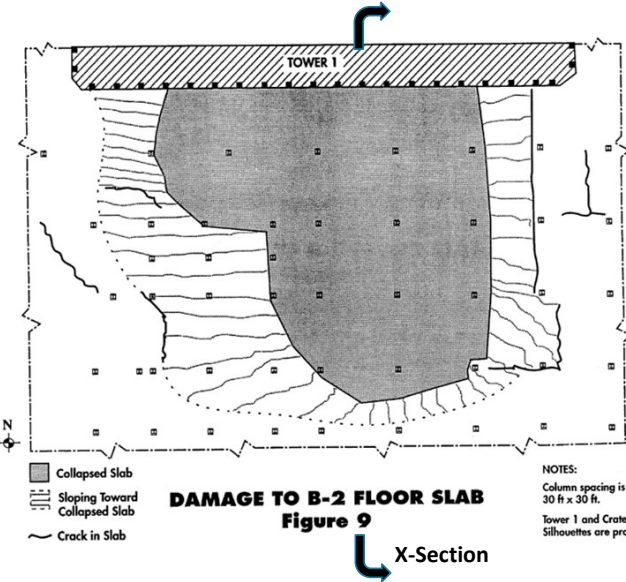


B-2 Level Damaged Tower Column and Missing Bracing Member

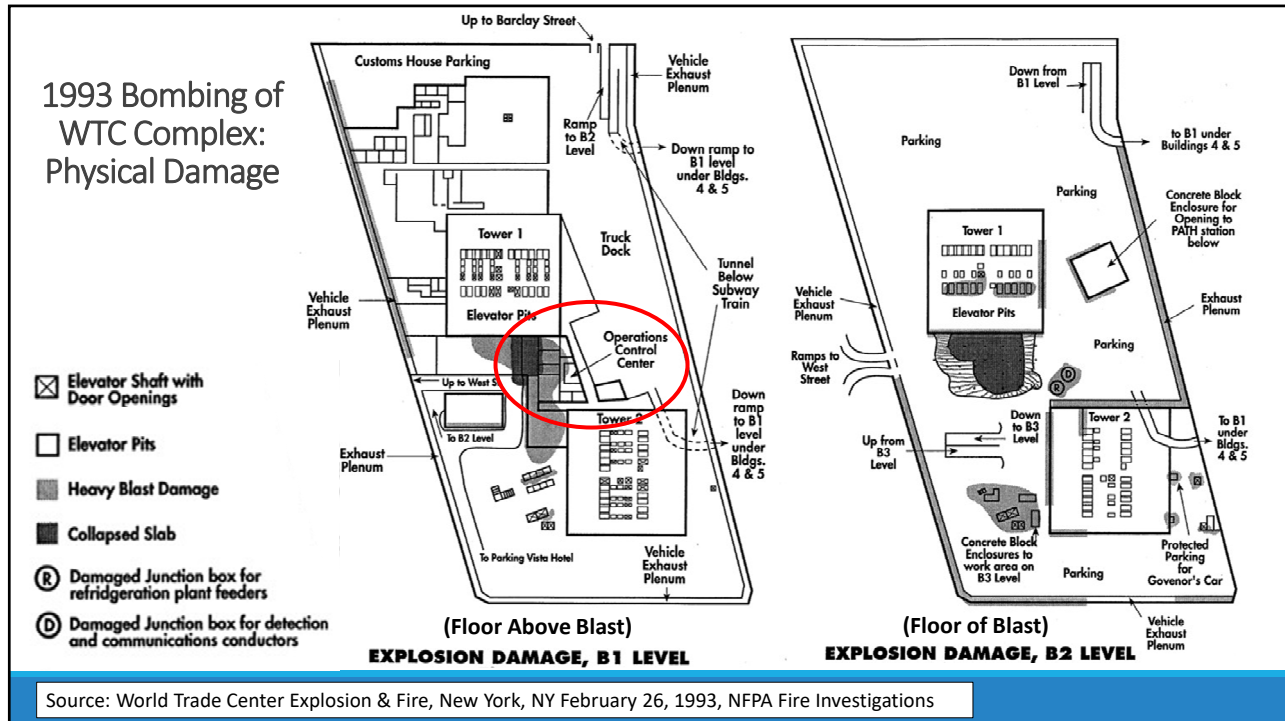
Partial Plan WTC Plaza Level

Source: World Trade Center Explosion & Fire, New York, NY February 26, 1993, NFPA Fire Investigations

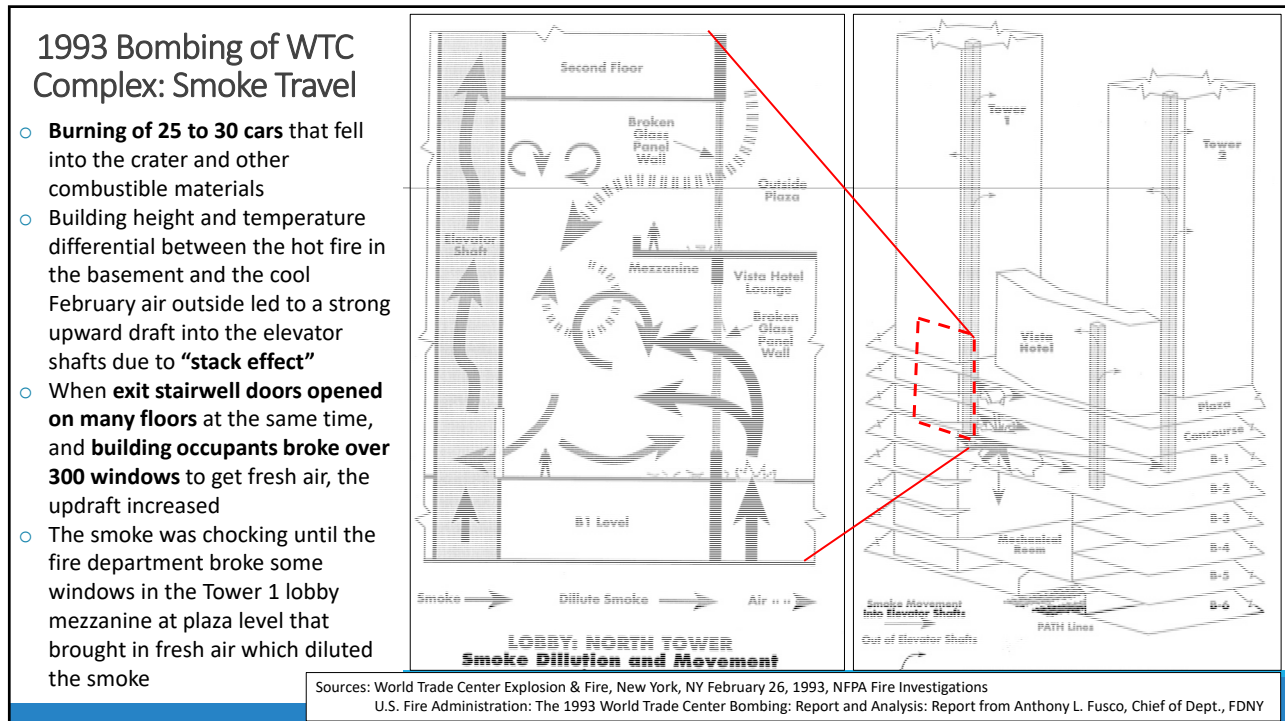
1993 Bombing of WTC Complex: Physical Damage



Source: World Trade Center Explosion & Fire, New York, NY February 26, 1993, NFPA Fire Investigations



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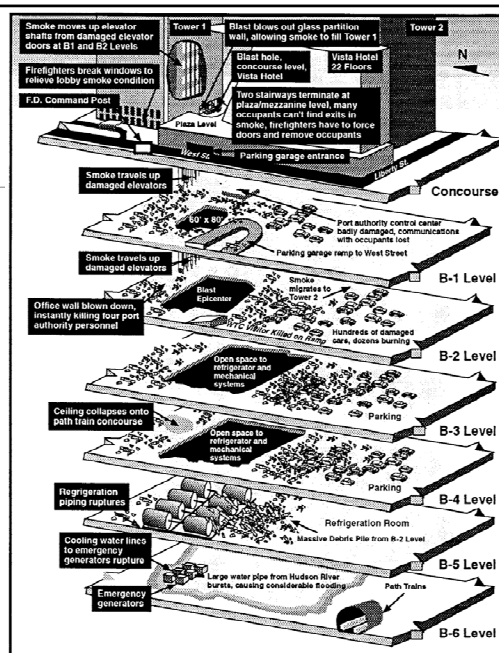


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1993 Bombing of WTC Complex: Damaged Emergency Operation Systems During Massive Evacuation

- Severe explosion impacted virtually every fire protection system in the complex: public address, fire alarm voice communications, and smoke detection were immediately inoperable
- Emergency generator in the basement shut down causing complete power electric failure to towers and elevators
- Generators shut down due to overheating since cooling system piping was ruptured by collapse
- Ruptured waterlines continued to flood the basement level
- Basement fire from stored combustibles was fed by fuel leaking from cars in parking garage, their gas tanks ruptured by the blast leading to heavy smoke driven by heat
- Facing heavy smoke on every floor due to the chimney stack effect in elevator shafts and without guidance from emergency communications, all building occupants began evacuating at the same time
- When evacuating occupants evacuated simultaneously the open stairwell doors increased the upward flow of smoke through the towers

Source: World Trade Center Explosion & Fire, New York, NY February 26, 1993, NFPA Fire Investigations



Source: U.S. Fire Administration: The 1993 World Trade Center Bombing: Report and Analysis: Report from Anthony L. Fusco, Chief of Dept., FDNY

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Lessons Learned from Evacuation of WTC Towers (NFPA Fire Investigations)

- This should be an impetus for the fire safety community to **re-examine the current design philosophies and future direction for high-rise fire technology.**
- The fire protection community should **re-examine the roles of redundant systems, separation criteria for vital equipment, systems maintenance** Consider increasing the reliability of fire protection features in “mega-high-rise” buildings.
- The **resulting smoke spread due to “stack effect”** ... should be carefully studied as one of the most important elements in the performance of fundamental fire safety concepts.
- **High rise building are not designed to be totally evacuated in an emergency.** They use a “defend in place” concept that only evacuates those floors immediately at risk from fire. **It is very dependent on a reliable communication system** which failed in this case [and closing stair exit doors to prevent smoke spread from the fire location].

[Note that significant changes were made to the WTC complex after the 1993 Bombing which included redundant circuits for the power, fire alarm and communications lines that run vertically in the towers, a back up fully redundant emergency operations center, and back up emergency generators.]

Source: World Trade Center Explosion & Fire, New York, NY February 26, 1993, NFPA Fire Investigations

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Damage from Explosion: WTC Damage - Level by Level - From Concourse to Level B-6



Damage at the WTC Concourse Level (Main Lobby Elevators in 1 WTC Seen in Distance). The Blast Vented Upward Through the Hole in the Floor. (The WTC Plaza Slab Above this Level Buckled Upward but Did Not Breach)



Damage at the B-1 Level Where the Was a Large Section of Floor Slab that Collapsed Adjacent to the Operations and Control Center

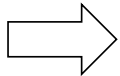
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WTC Damage B-2 Level



Collapse of Utilities from Blast at B-2 Level
NY Telephone Company major telephone exchange at the WTC complex providing telephone service to Lower Manhattan also providing service for air traffic control systems at the three major NY-NJ airports

Vehicle at B-2 Level Overturned by Blast Pressure



Remains of Burning Vehicle at the B-2 Level



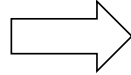
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WTC Damage B-2 Level



Sloping Edge of the Bomb Crater at B-2 Level

4- Story Tall
Unbraced
Column in the
Center of the
Crater Created
by the Bomb
with Some
Also
Supporting
Vista Hotel



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WTC Damage B-3 and B-4 Levels



Collapse of Parking Garage Walls & Finishes
From B-3 Level Fall onto the PATH Station Fare
Collection Zone on B-4 Level



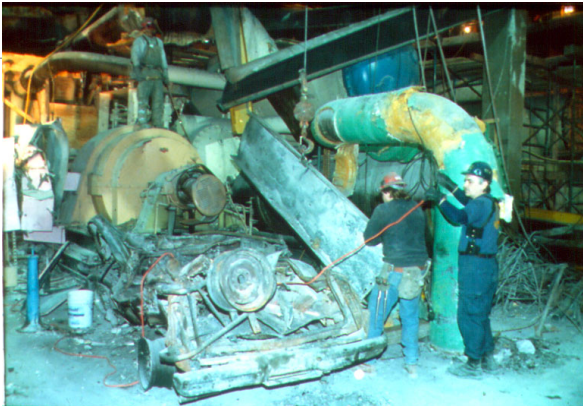
Looking Down on B-4 Level PATH Fare Zone
From B-3 Level After Debris Clean Up. PATH System was
Found to be Operable.

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WTC Damage at B-5 Level



Fire Charred Concrete Floor Slabs and Collapsed Steel Framing Lying on Top of the Refrigeration Equipment (Chillers and Piping) at Bottom of Crater at B-5 Level



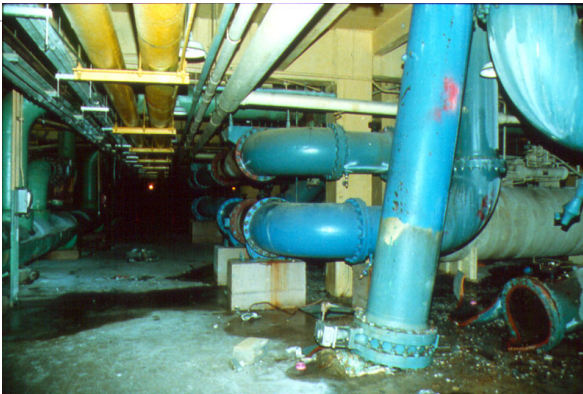
Chassis of Blast Damaged Vehicle and Collapsed Steel Framing Lying on Top of the Refrigeration Plant

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WTC Damage

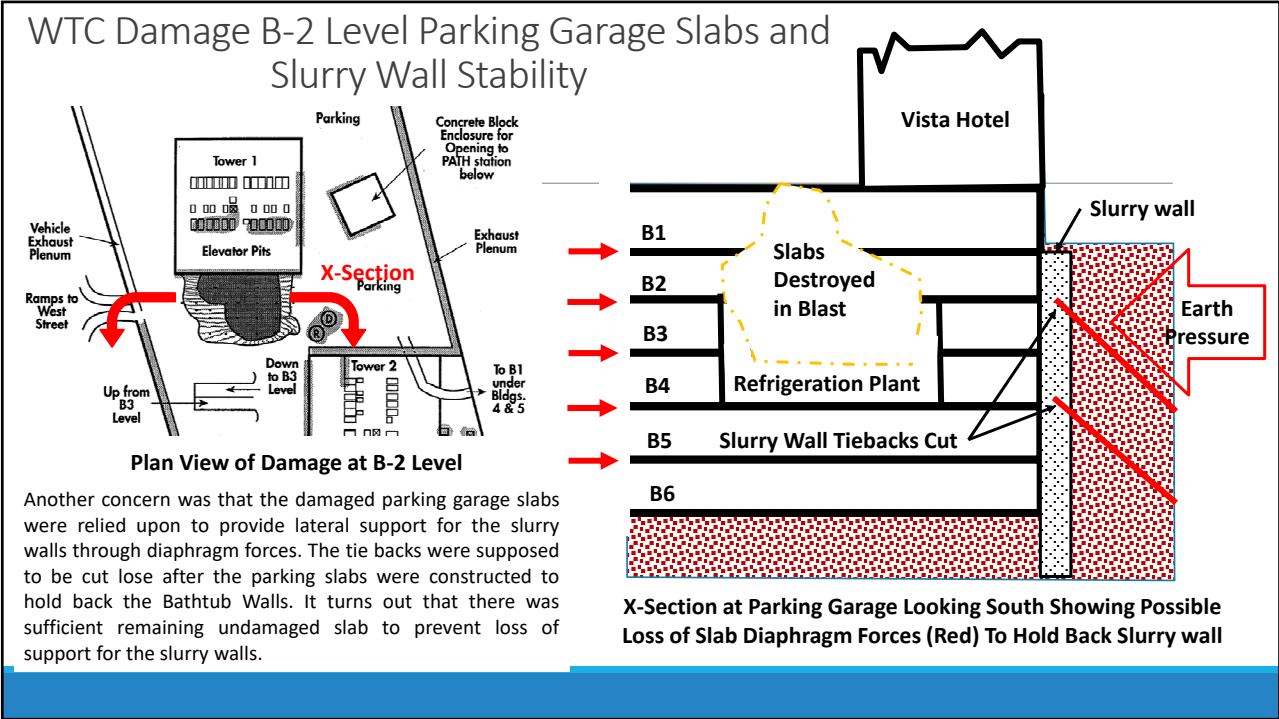


Collapsed Slabs from the B-1 and B-2 Levels Crushed the Refrigeration Plant Equipment on the B-5 Level



Damaged Piping at the B-6 Level that Supplied Hudson River Water as Coolant to the Chillers Created Flooding of the B-6 Level Where the Emergency Generators Overheated

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The Pressure is On: Soot Filled WTC Twin Towers Unoccupied Without Essential Utilities and Losing Rental Income Estimated at \$1 Million Per Day

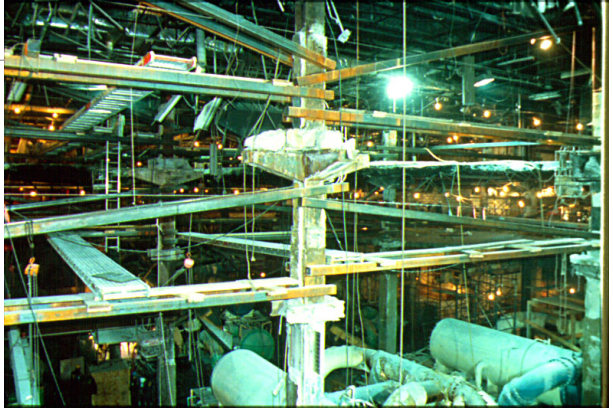
- One of many Port Authority meetings held between the Chief Engineer, the Executive Director's staff and staff from their engineering department
- Organizing and Mobilizing to Perform Damage Assessment, Design and Construction of Temporary Shoring and Bracing
- Retaining contractors and engineers on an emergency basis to construct shoring and bracing, perform debris removal
- Developing Project Management and Construction Management Plans and Schedules
- Preparing Design and Construction Plans for Restoration and Replacement of Building Subgrade and Utilities for the Twin Towers
- Prepare "Backup Plan" for construction of Temporary Outdoor Refrigeration Plants in case there are delays in the schedule.

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Temporary Shoring and Bracing for Safety and Stability During Debris Removal, Demolition, and Reconstruction



Iron workers entering the subgrade "crater" through an access hole cut through the Vista Hotel Concourse Lobby. They will use Spider Baskets to Install Steel Bracing Members on Unbraced Columns Supporting the Vista Hotel



Out of Concern for the Stability of the 4-Story-Tall Unbraced Columns in the "Crater" Steel Bracing Members Were Designed and Installed Before the Debris at the Bottom of "Crater" Was Removed. The Debris May Have Been Stabilizing the Columns.

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WTC Subgrade Debris Removal Monitored by FBI (Needed to Maintain Legal Trail of Any Evidence)



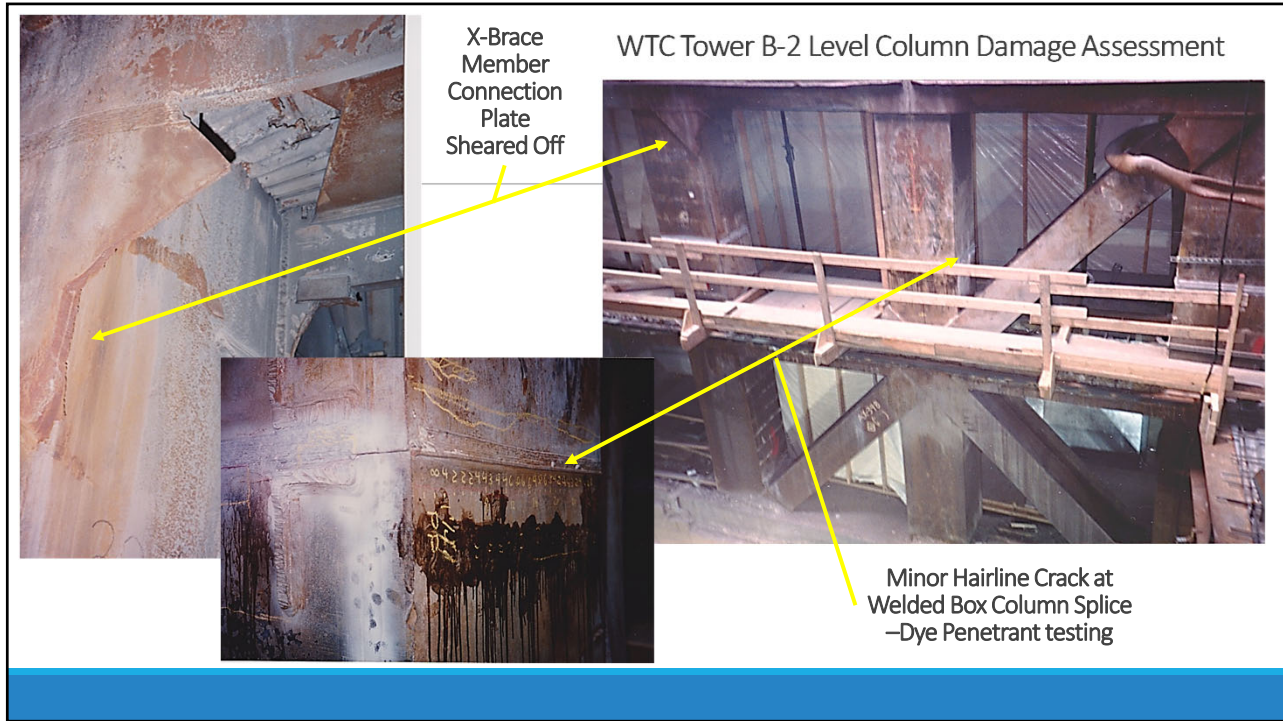
Debris Being Placed in Bins at B-5 Level to be Transported Off-Site for Inspection by FBI and ATF



Damaged Sidewalk Slab at Plaza Level Removed (top) to Hoist and Load Debris on Trucks to FBI Inspection Site



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WTC Tower B-2 Level Column Damage Assessment and Repair

Decisions Affecting Tower Column Repair

- Perimeter Tower Columns at B-2 level were Massive Welded Steel Box Columns With Walls Several Inches Thick
- Concern that center column hairline crack at welded joint may have shed some of its load to adjacent columns to left and right
- Decided to perform X-ray diffraction testing to measure the stress in the three adjacent columns before repairing the center column
- It was found that the vertical surface stresses in the columns were actually in tension, not compression, due to the residual stress from weld shrinkage during cooling of the large continuous shop welds
- The size of the tower perimeter columns was based upon the need to stiffen the tower to control lateral deflection under wind loading and was not governed by dead, live and wind load stress in the columns (Important relative to 9/11 attack)
- It was decided to simply repair the cracked weld and bracing

Note: X-ray Diffraction Measurements by Proto Automated NDT Systems & Services

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Installation of Structural Steel and Continued



Steel Framing Being Installed to Replace the Collapsed B-2 Level Floor system That Spans Over the Refrigeration Plant



Steel Decking Being Installed Over the Refrigeration Plant

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Installation of Structural Steel and Continued



With Steel Decking In Place Work on Repairing the Refrigeration Plant Could safely Proceed



After Placement of Reinforcing Steel on Top of Steel Decking Structural Concrete is Pumped, Cast and Finished

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Completed Temporary Refrigeration Plants on the Surrounding Streets



The Completed Temporary Refrigeration Plant on Liberty Street Extended from 2 WTC (Left Photo) to Church Street (Right Photo). The Internal repairs to the permanent WTC refrigeration plant were completed in October 1993 when, after the cleaning of all the soot from within all floors of the Twin Towers, by an army of cleaning workers, the Buildings were opened for re-occupancy.

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Assessment of Learning 2 of 2

1. Identify one of several reasons why the smoke spread through the WTC Towers so fast:
 1. The “Stack Effect”
 2. Stairwell exit doors on many floors open at the same time
 3. Building occupants broke windows to get fresh air
 4. Burning of many cars that fell into the crater

2. How severely damaged was the tower building column at the B-2 level that took the brunt of the explosive force from bomb?

The column had only minor damage from a hairline crack.

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How The Towers Fell – Part 1/3
How the WTC Twin Towers Were Constructed &
Lessons Learned From the 1993 Bombing

Questions?

