Progressive Collapse – Historical Perspective

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History of Progressive Collapse

- **Structural collapse caused by commonly encountered loading (gravity, seismic, wind, etc.) has always been an issue for designers**
- **The term “progressive collapse” and design to prevent it are recent occurrences in engineering design**
- **Why has progressive collapse become an issue?**

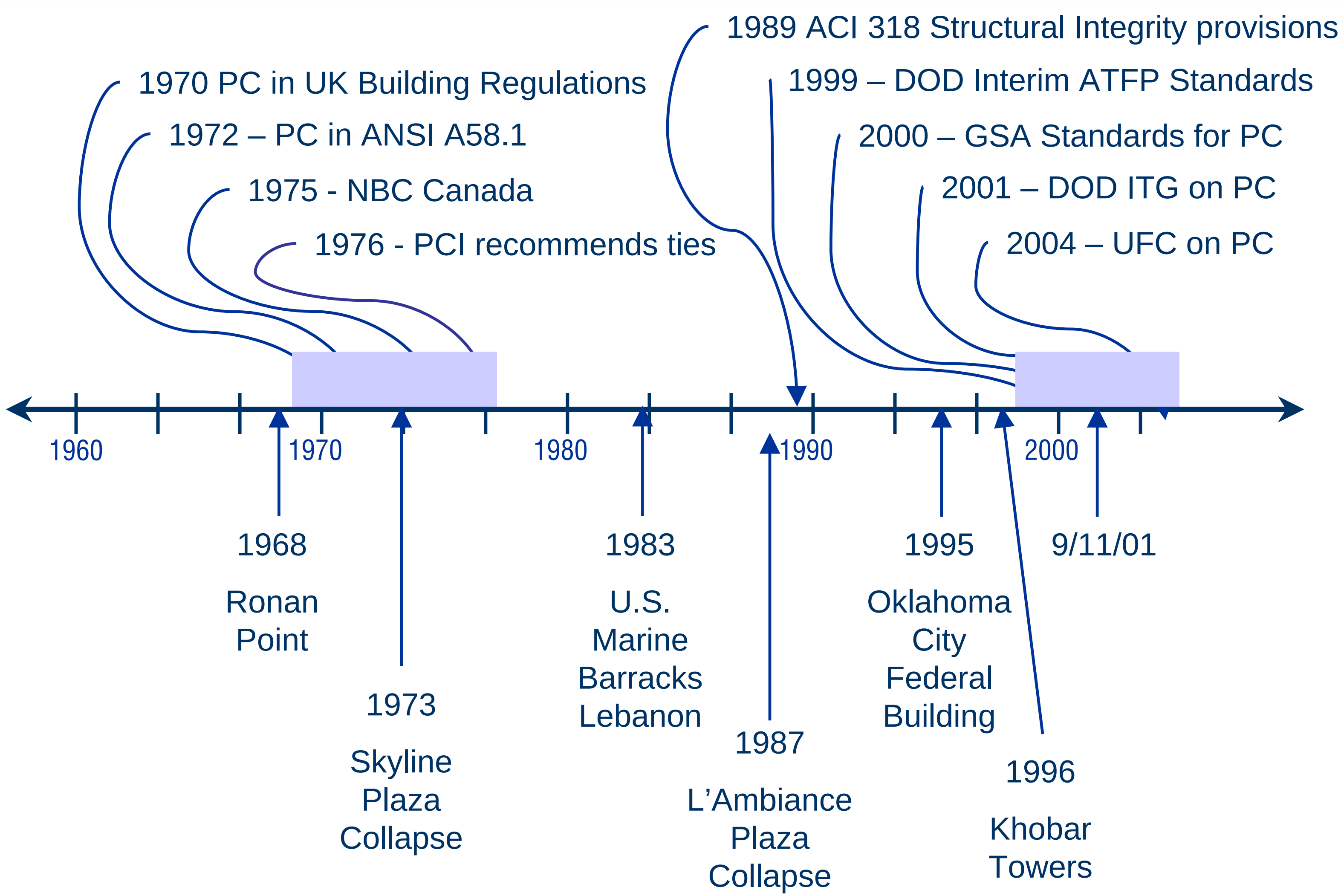
Changes in Structural Design

- Many suggest that past structures were able to resist abnormal loads due to inherent strength and continuity, however, recent developments in optimization, innovative framing systems, and refinement of analysis techniques have resulted in structures with a considerably smaller margin of safety.
- Others would suggest that framing systems designed for ease of construction possess less inherent continuity leading to less resistance to abnormal loads (I.e. less load redistribution)

History of Progressive Collapse

- By examining the historical context for the problem, it is easier to understand development of solutions
- Timeline of important events compared against evolution of design/code requirements best illustrates how we got here
- Many events may not be truly progressive collapse, but still influence the development of guidelines nonetheless

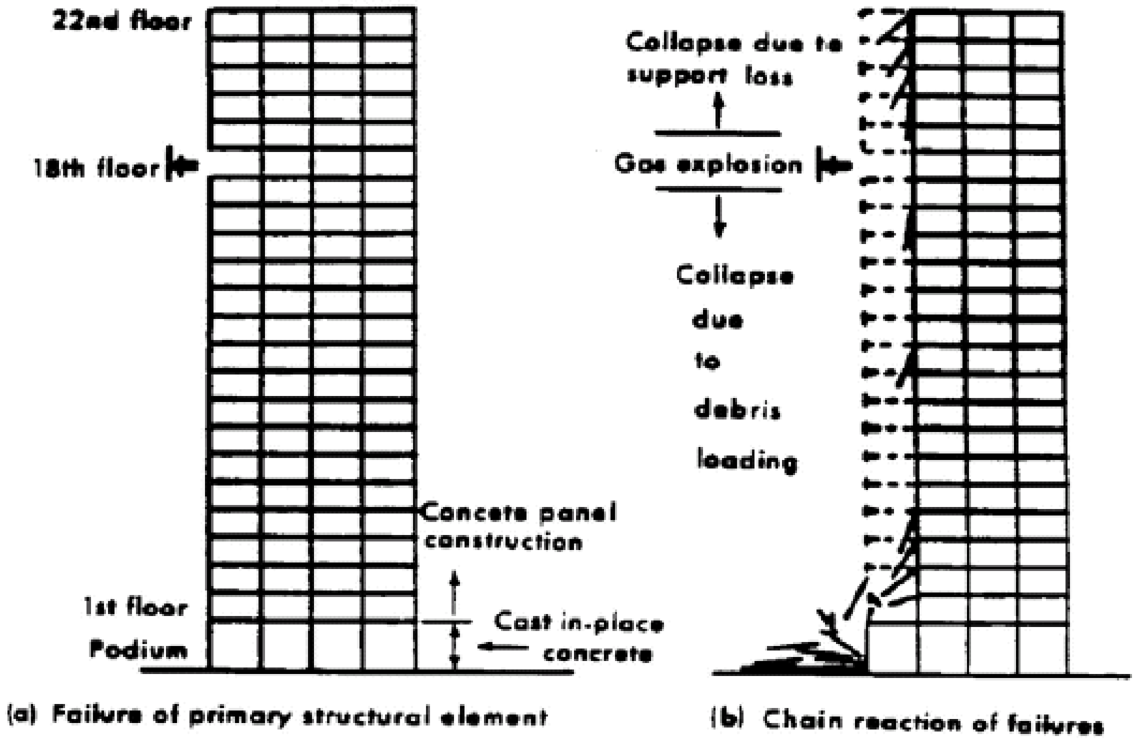
Progressive Collapse Timeline



Ronan Point Apartments

- Watershed event for progressive collapse
- 22 story precast panel construction supported by cast in place concrete structure including parking garage
- Gas explosion occurred in 18^{th} story apartment
- Wall panel blew out, causing loss of support of panels on $19\text{-}22^{nd}$ flrs
- Debris of upper floors caused each floor below to successively collapse

Ronan Point Apartments



Schematic of the Ronan Point Collapse, Modified After Dragosavic (15).

Ronan Point Apartments

- **Inquiry**
  - **Found no violation of any applicable building standard, nor defect in workmanship**
  - **Building standards gave detailed requirements for design of elements, but little guidance on stability of entire structural system**
  - **Joint forces resisted solely by bond, friction, and gravity**
  - **Upon removal of the walls, connection above could not redistribute loads since they were designed only for compression**
- **There were some existing building standards and codes of practice that contained general warnings and guidance on design of large panel structures that may have mitigated some of the problems at Ronan Point**

Ronan Point Apartments

- **Interest in progressive collapse was immediately created in the United Kingdom and other nations**
- **Changes to UK Building Regulations**
  - **November 1968 – UK Ministry of Housing and Local Government issued "Standards to Avoid Progressive Collapse – Large Panel Construction"**
    - Had Alternate Load Path, Continuity, and Accidental Load
  - **April 1970 – Standards became part of mandatory Building Regulations**
  - **1974 – Provisions of structural ties entered British Standards**

Ronan Point Apartments

- Ronan Point generated research and discussion in several countries including the United States
- Although discussion of progressive collapse has continued throughout decades since Ronan Point, most of the authoritative papers were published within a few years of the event
- United States developments
  - ANSI A58.1 addressed issue by 1972
  - PCI provided recommendations on ties in precast concrete bearing wall buildings in 1976
  - Later events of 1970s influenced U.S. developments as well

Skyline Plaza

- March 2, 1973
- While concrete was being placed on the 24th floor and shoring removal was occurring on the 22nd floor a collapse occurred for the full height of the tower
- Impact of debris also caused horizontal progressive collapse of entire parking garage under construction adjacent to the tower
- 14 workers killed, 34 injured

Skyline Plaza

- Tower was reinforced concrete flat plate construction
- Study of failure indicated premature removal of 22nd floor slab shoring lead to punching shear failure of the slab around one or more columns at the 23rd floor
- The weight of debris caused the failure of all the lower floors for the full height

Marine Barracks, Lebanon

- **One of the first large scale terrorist attacks on DoD facilities causing significant collapse and causalities**
- **Estimated bomb equivalent weight of 12,000 lbs. TNT**
- **241 U.S. personnel killed, 80 wounded**
- **Although no direct changes were made to U.S. national building codes or DoD design criteria, the event began a history of attacks that eventually influenced design to prevent progressive collapse**

Murrah Federal Building, Oklahoma City

- April 19, 1995
- Explosive charge equivalent to approximately 4000 lb. TNT detonated on north side of building
- Building was designed in early 1970s
- Nine story, reinforced concrete OMRF, one way slab system
- Transfer girder at third floor level supporting intermediate columns, providing 40’ clear span for first two levels

Murrah Federal Building, Oklahoma City

- Analysis based on the approximated blast loading indicates that the column nearest the explosion (G20) would have failed by brisance or shattering
- The columns on either side of this column (G16 and G24) were found to have exceeded their shear strength and failed in shear. The loss of these three columns resulted in the transfer girder being unsupported for a distance of approximately 160 ft.
- The transfer girder then failed, and the resulting progressive collapse of all of the floors above extended through most of the north half of the footprint and 35 feet into the building.
- Roughly half of the occupiable space of the Murrah building collapsed

Murrah Federal Building, Oklahoma City

- **Whether this facility experienced progressive collapse is often debated based on whether initial damage was “local” or global in nature**
- **Most agree that changes in design to eliminate transfer girder, add continuity, and add ductility would have diminished extent of damage**
- **This event precipitated the adoption of security criteria by the General Services Administration which included design requirements to prevent or reduce the likelihood of progressive collapse (Nov. 2000)**
- **Event also influenced decision of DoD to incorporate progressive collapse prevention into AT criteria**

Khobar Towers

- June 25, 1996
- Terrorist bombing of barracks facility – estimated equivalent weight of 20,000 lb TNT
- 19 fatalities, 500 wounded
- Many believe structure is example of preventing progressive collapse
- “Downing report” following attack lead to development of specific force protection measures for DoD, including the DoD minimum AT standards for buildings

Khobar Towers

- So even though, structure did not collapse, Khobar Towers and the preceding terrorist attacks directly lead to the development of DoD minimum standards for buildings
- These standards addressed progressive collapse prevention for the first time for DoD

World Trade Center, 2001

- September 11, 2001
- Two aircraft were crashed into the two World Trade Center Towers
- This single event lead to the greatest public exposure of the potential for inherent weakness in structures when exposed to unexpected or extreme loading
- 10 major buildings experienced partial or total collapse

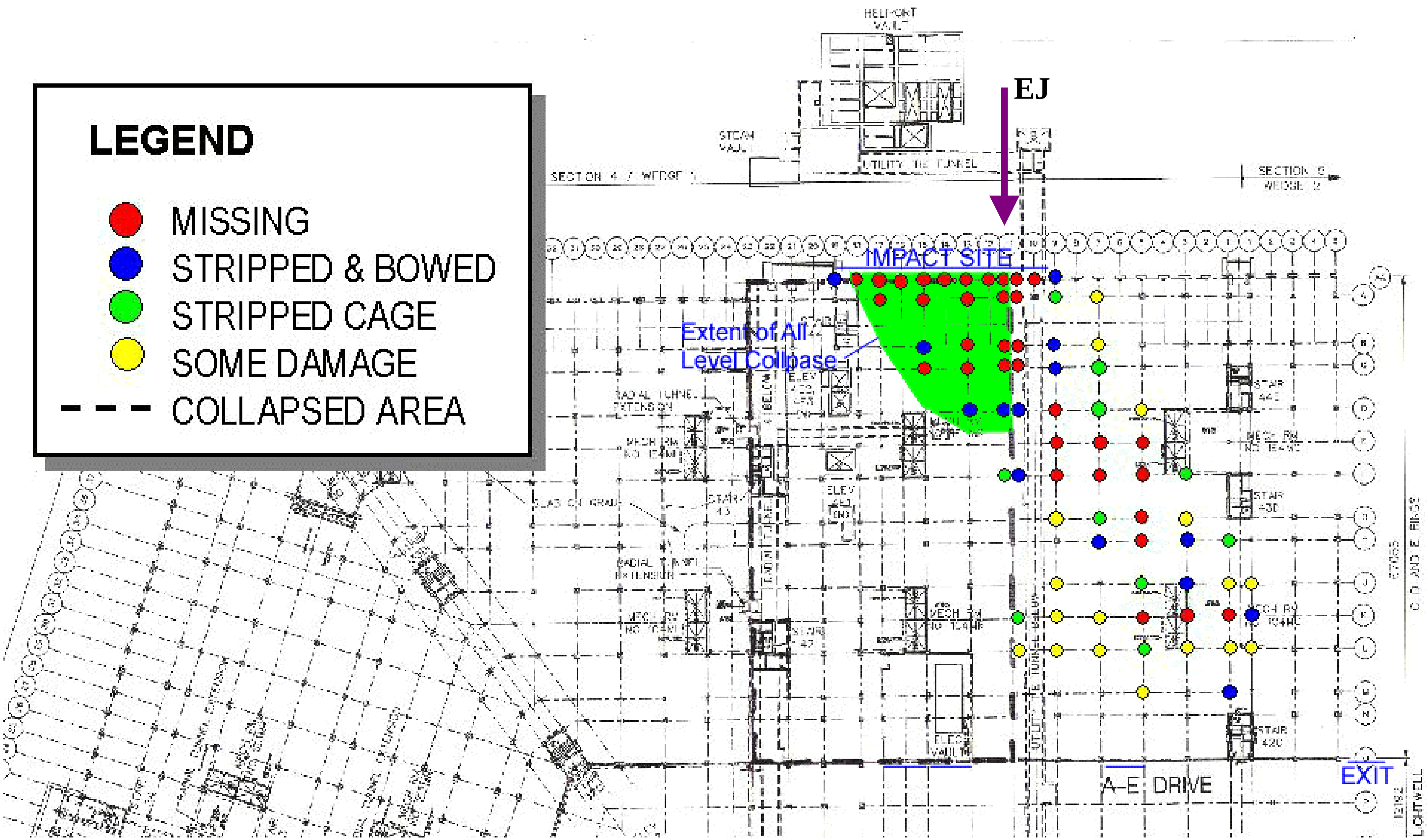
World Trade Center, 2001

- The events of September 11, 2001 served to focus the engineering community once again on the issue of progressive collapse
- Ironically, the events on that day show progressive collapse adverted in many cases. The towers themselves were able to withstand the initial loading from the impact of the airplanes, only to succumb at a later time due to the additional loading/weaknesses created due to the fire-structure interaction
- In addition, several buildings surrounding the towers received extraordinary damage from debris loading, but they did not have general collapse, i.e. they did not experience progressive collapse. One example is the Banker's Trust Building
- Nonetheless, the events at the WTC will always be linked to the issue of progressive collapse as it rejuvenated the attempts to address the issue of progressive collapse prevention

Pentagon, September 11, 2001

- An aircraft was crashed into the Pentagon on 9/11/01
- As was the case in the WTC, the structural system as a whole showed great ability to redistribute load with only a small area of local collapse
- A Building Performance Assessment Team (BPAT) studied the damage for lessons learned from the performance of the structure

Pentagon, September 11, 2001



Pentagon, September 11, 2001

- **Findings : collapse limited by following factors**
  - **Redundant and alternative load paths of the beam and girder framing system**
  - **Short spans between columns**
  - **Substantial continuity of beam and girder bottom reinforcement through supports**
  - **Design for 150 psf warehouse live load in excess of service load**
  - **Significant residual load capacity of damaged spirally reinforced columns**
  - **Ability of exterior walls to act as transfer girders**

Pentagon, September 11, 2001

- **Recommendations for Design and Construction – features validated to reduce collapse from severely abnormal loads:**
  - **Continuity, as in the extension of bottom beam reinforcement through the columns**
  - **Redundancy, as in the two-way beam and girder system**
  - **Energy-absorbing capacity, as in the spirally reinforced columns**
  - **Reserve strength, as provided by the original design for live load in excess of service**
- **Report noted need for effort to accumulate research and practical experience in area of structural robustness so an authoritative guide can be prepared for the design community**

Conclusions from Timeline

- **Developments in prevention of progressive collapse have closely followed behind the events initiating interest and development stagnated during times of reduced incidents or less dramatic collapses**
- **Current driver for increased interest in prevention of progressive collapse or enhanced structural integrity by U.S. government agencies is perceived increase in risk of abnormal loads associated with terrorism**

- **Question: Are there any good news stories from history?**

Events following British Standard changes

- Buildings designed in accordance with the modified British standards (1974) have been exposed to abnormal loading
- This provides qualitative evidence of potential effectiveness of British provisions
- Examples:
  - Exchequer Court, St. Mary's Axe, London 1992
  - Kansallis House, Bishopsgate, London 1993

Exchequer Court

- Semtex bomb explosion 6 meters from building
- Exchequer Court was a "modern" steel frame building with in-situ concrete floors
- Braced frame construction, so all connections were designed for shear only, except design had to provide tying forces in accordance with British standards
- Connections were flush-end plate type, shear connections
- Building was significantly damaged but did not suffer collapse

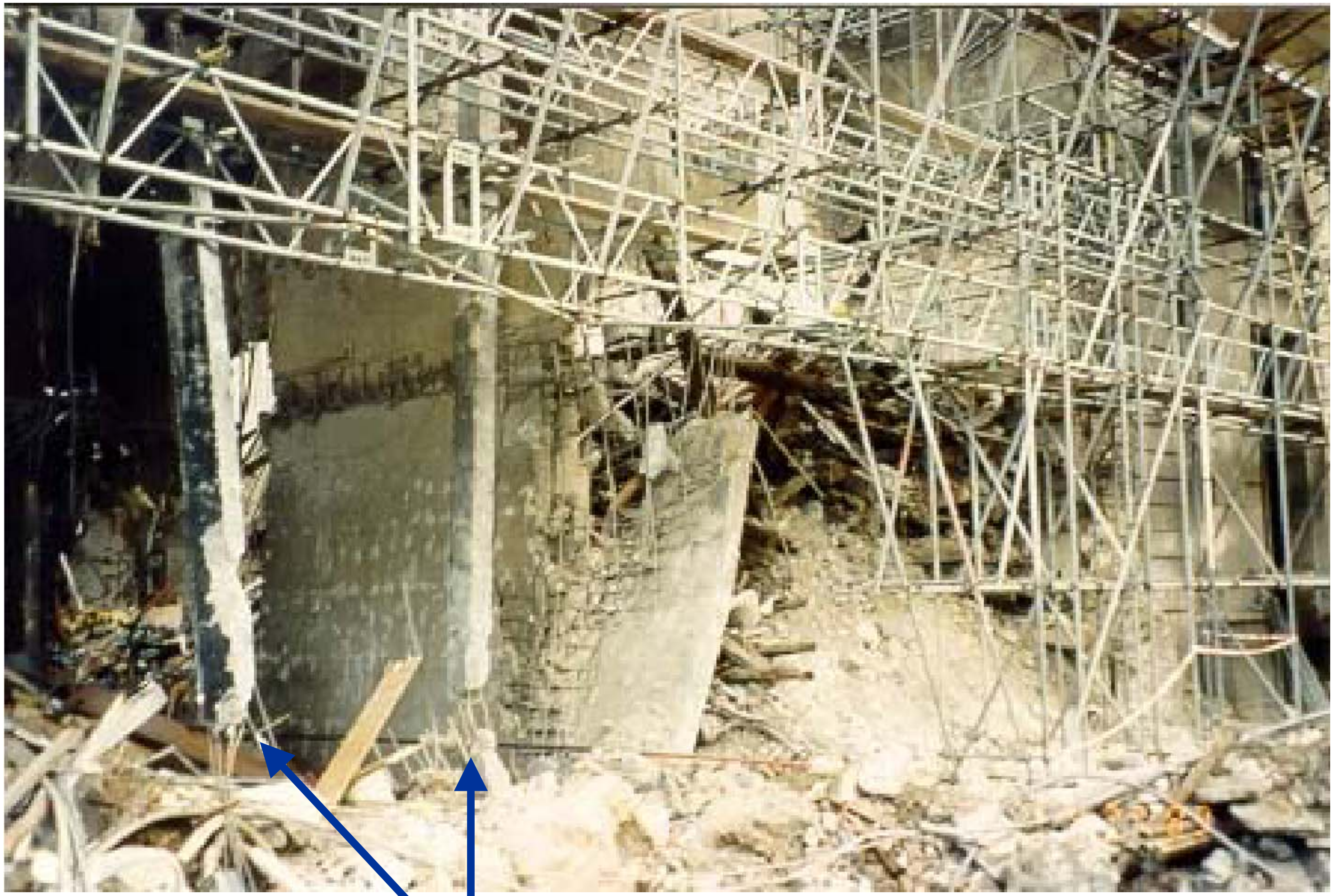
Exchequer Court

- Column Displacements were found of 125mm and 406mm for two of the first floor columns
- Some of the edge beam to column connections failed in shear

Kansallis House

- Constructed early 1980's of cast in place reinforced concrete, eight stories high. Reconstituted stone wall cladding.
- The perimeter beam was a 575mm deep by 300mm wide reinforced concrete beam. A grid of reinforced concrete columns supported each floor and along the side of the building nearest the explosion the columns were 1200mm wide and 300mm deep.
- Bomb exploded within 6 meters of building (one report indicated approx. 1000 lb. fertilizer)
- Three load bearing columns and 127m^2 of the 1st floor and 73m^2 of the 2nd and 3rd floors immediately above these columns were lost. In spite of this damage the majority of the building remained intact.
- The mechanism that enabled the remaining part of the building to bridge over the missing columns is unknown but clearly the design provisions provided sufficient redundancy in the structure to allow such bridging to occur.

Kansallis House



Column Failure