In one sense, these two buildings provide a roughly equivalent set of circumstances for comparison; both are (or were) reinforced concrete buildings subjected to extreme events. However there were significant differences in the nature of the attacks and in the materials properties, layout, and design of each building. The comparison given here is qualitative only.

Pentagon Source Material:

Shown is a plan view of the beams and girders for an outer section of ring E. The exterior of ring E would be on the right hand side of the figure. Note that the exterior wall has extra columns. These are necessary to support the weight of the heavy limestone cladding.

Note that the columns used spiral confinement. Spiral confinement was used so that the columns could have a higher allowable stress (1930’s RC design would have been an allowable stress procedure) to hold the high specified live load.

Spiral confinement was not used for any of its other benefits: enhanced ductility and load redistribution capability.
The Pentagon Building Attack

**Girder Details**
- Bottom Bars Extended into Columns
- Close Stirrup Spacing Throughout Length

*The girder and beam details provided ductile performance and redistribution of load.*

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**The September 11, 2001 Attack:**
- The aircraft was a Boeing 757-200. (wingspan of 125' and tail height of 44.5')

- At the time of the impact, it was travelling at 780 ft/sec, weighed 181,520 lb, and had 5,300 gal of fuel. (kinetic energy = 1720 million ft*lb)

- The aircraft debris decelerated at a rate of approximately 30g as it impacted with the building.

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**The September 11, 2001 Attack:**
- 64 people aboard the aircraft and 125 people in the building were killed.

- The aircraft struck a recently renovated portion of the building (additional facade support and blast resistant windows had been installed)

- Structural damage from impact, explosion, and sustained fire.
Corridor 4 is on the right, Corridor 5 is on the left.

Point out the extent of fire damage to the structure.

The furthest spread occurred along the roofs – ironically facilitated by the concrete roof which prevented fire fighters from accessing the crawl space where the fire was.

The figure shows the wedge of damage created by the impact. Damage and debris were found approximately 310 feet from the point of initial impact - a hole in the wall of ring C leading to AE drive.

The heaviest objects from the plane were found the furthest along the impact trail. The front landing gear and the “black box” were found at the hole to AE drive. Additionally, the plane inverted itself as it decelerated, with items at the front of the craft deposited near the head of the impact trail and items at the back of the craft found further along. Human remains belonging to the terrorists and items belonging to the cockpit were found in ring E. Objects from the rear of the fuselage were found in rings D and C.

Figure 3.10, page 17 from the Building Performance Report.
Figure 3.9, page 16 from the *Building Performance Report*.

Slide 13

The Pentagon Building Attack

Figure 1.3, page 4 from the *Building Performance Report*.

Slide 14

The Pentagon Building Attack

- The damaged portion of the Pentagon collapsed after 20 min. due to fire damage inflicted to the structural concrete
- 86% of the jet fuel (30,400 lb) was estimated to have entered the building
- Estimations place the peak temperature of the fire at 1500 to 1600 °F

Slide 15

The Pentagon Building Attack
Slide 16

The Pentagon Building Attack

Figure 5.1, page 24 from the Building Performance Report.

Slide 17

The Pentagon Building Attack

Figure 5.4, page 25 from the Building Performance Report.

Slide 18

The Pentagon Building Attack

Figure 5.8, page 27 from the Building Performance Report.
The Pentagon Building Attack

Slide 19

Figure 5.16, page 30 from the Building Performance Report.

Slide 20

After Figure 7.9, page 53 from the Building Performance Report.

Slide 21

Figure 7.5a, page 48 from the Building Performance Report.
The Pentagon Building Attack

Slide 22

Note the necking of the longitudinal reinforcement at the fracture points.

Figure 7.5b, page 48 from the *Building Performance Report*.

Slide 23

Two columns found in this condition: no concrete left – just an empty cage.

Slide 24

Significant Impairment - Severe deformation of the column and loss of the majority of cover.

Many columns had significant rotation at top and bottom connections.

Figure 5.21, page 32 from the *Building Performance Report*. 
Slide 25

Loss of the cover impaired the ability of the columns to endure the fire.

Note the discoloration of the concrete from the fire.

Figure 5.20, page 31 from the Building Performance Report.

Slide 26

Some impairment - Partial loss of cover.

Insignificant deformation of the column.

General integrity of the core was maintained.

Figure 5.18, page 31 from the Building Performance Report.

Slide 27

Fire damaged column - This column shows signs of fire damage: discoloration and spalling of concrete.

Fire damage can cause loss of concrete strength even when outward signs of damage seem minor.

Figure 5.19, page 31 from the Building Performance Report.
Eventually, they rebuilt rings E, D, and C between corridors 4 and 5.

This photo is from Corley et. al., Fig. 1, pg. 100.

Murrah Source Material:


Sozen, et. al., “The Oklahoma City Bombing:


Four large columns along the south side (G12, G16, G20, and G24) were used to create an open front along N.W. 5th Street. These columns extended for the 1st and 2nd floor and supported a transfer girder upon which sat smaller column framing similar to the spacing along the two interior column lines shown above.

Other notes: The building used one-way slabs for the floors with beams running north-south. The outer walls on the east and west, and the rear stairwell of the building contained structural shear walls.

The four large northern exterior columns were most effected by the bomb blast and hence the columns of interest here. The columns had a 3.5% reinforcement ratio (high).
The Pentagon Building Attack

The April 19, 1995 Attack:
- Homemade truck bomb exploded just outside the north face of the building
- 4800 lb of ammonium nitrate and fuel oil
- Approximately a 5,000 lb TNT equivalent explosion
  (Bomb yield estimated by the crater size: 7' deep, 28' diameter)

The Pentagon Building Attack

The April 19, 1995 Attack:
- Caused air blast and ground shock loading on the surrounding buildings
- 163 people were killed in the building, primarily by progressive collapse of the building (4 other people killed outside the building)
- $652 million property damage (Extensive broken glass, damaged facades, and structural damage to surrounding buildings)

The Murrah Building Attack

This photo is from ENR, pg. 18.
Slide 36

This figure taken from Hinman, Fig. 1.25.
Building 9 is the Murrah Building
Building 6 is the Athenian Restaurant

Slide 37

The day care center was on the 2nd floor.

Slide 38
Brisance is a general term referring to shattering of any brittle material, not a term particularly related to concrete.

Column G20 would not have survived in any case unless it was shielded in some way from the high overpressure of the bomb.

Columns G16 and G24 may have survived if they had higher shear capacity and flexural ductility - such as if they had spiral confinement rather than ties.
Slide 42

The Murrah Building Attack

This photo is from Pendergast, pg. 43.

Slide 43

The Murrah Building Attack

This photo is from Hinman, Fig. 1.7.

Slide 44

The Murrah Building Attack

Conclusions of the Investigative Engineers:

"...if the 1976 Murrah building had been built using today’s seismic building design details, as much as 50 to 80 percent of the structural damage, and presumably the fatalities, could have been prevented."

"...the bomb blast to the Murrah building was not devastating by itself...it just so happened that it was located at a critical point which undermined the whole structure of the building.”

Gene Corley - Testimony before the Public Buildings and Economic Development Subcommittee of the U.S. House of Representatives
The Murrah Building Attack

Conclusions of the Investigative Engineers:

- The use of spiral confinement would have greatly enhanced the shear capacity of columns G16 and G24, possibly allowing them to survive the attack.
- Enhancements to the details of the slabs and girders would include more continuity of reinforcement.
- The cost of these measures is minor compared to the overall cost of the building.

Other Factors:

- Placement of the building from the street: additional space between the building and the street would have greatly reduced the overpressure load.
- Framing Plan: less reliance on individual critical elements. A less open front with more columns would have made the structure less dependent on the survival of any one column element.
- Slab Performance: the blast caused pressure underneath the slabs, pushing them upward and subjecting them to moments in reverse of those they were designed for.

Comparison - Pentagon vs Murrah Building

- The performance of the Pentagon is generally considered ideal in comparison to the Murrah building.
- The Pentagon lost more columns from the initial attack, but overall lost less proportion of tributary area supported by those columns.
- The ductile performance of the Pentagon columns, beams, and joints played a key role in its performance.