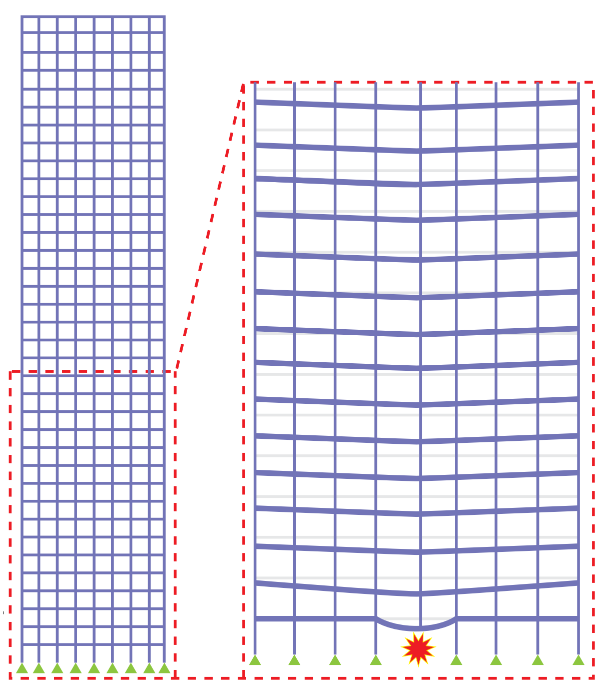
Vulnerability of Tall Buildings to Progressive Collapse

By Vincenzo Melchiorre, P.E.

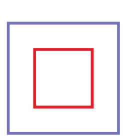
The vulnerability of high rise structures to progressive collapse after a blast event has become a growing concern among building owners and government entities, particularly following the collapse of the Alfred P. Murrah Federal Building in 1995 and the World Trade Center towers in 2001. High rise buildings are generally considered more susceptible to terrorist attacks due to their location as well as iconic stature. Furthermore, ground floor columns are particularly vulnerable to failure due to their proximity to public streets and to the explosion source. Loss of even one of these columns can cause significant damage leading to progressive collapse.

Design of high rise buildings for conventional loading, such as seismic and wind, inherently provides a certain level of resistance to progressive collapse. High rise buildings typically include two or more lateral resisting systems that act in a complimentary fashion to provide required strength and stiffness to resist seismic and wind forces. These systems offer a level of redundancy that is critical for progressive collapse resistance.

We will look at four gravity and lateral resisting structural systems of high rise buildings and evaluate their inherent resilience to progressive collapse after loss of a main support at the ground level. The structural types are grouped into two broad categories based on whether or not they contain exterior moment frames, and are further broken down into their specific gravity and lateral systems including: 1) moment frame with central core, 2) tube within tube or bundled tube, 3) central core with exterior multistory trusses, 4) central core with outrigger trusses, and 5) central core only. All building systems are assumed to include ductile detailing typical in seismic regions. Systems in which ductile detailing is not provided have little resistance to progressive collapse and will likely experience wide-spread shear failures which is beyond the scope of this article.

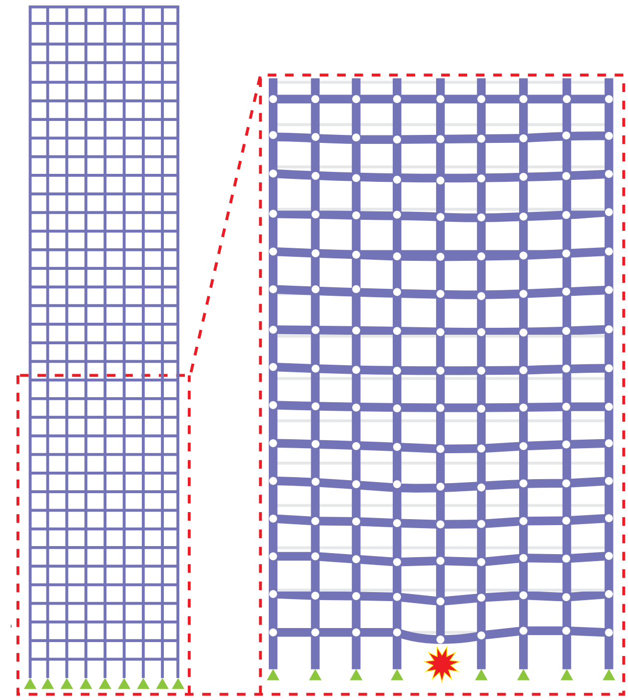


Exterior Elevation



Plan

Figure 1: Moment Frame with Interior Core & Structural Response for Loss of Perimeter Column.



Exterior Elevation

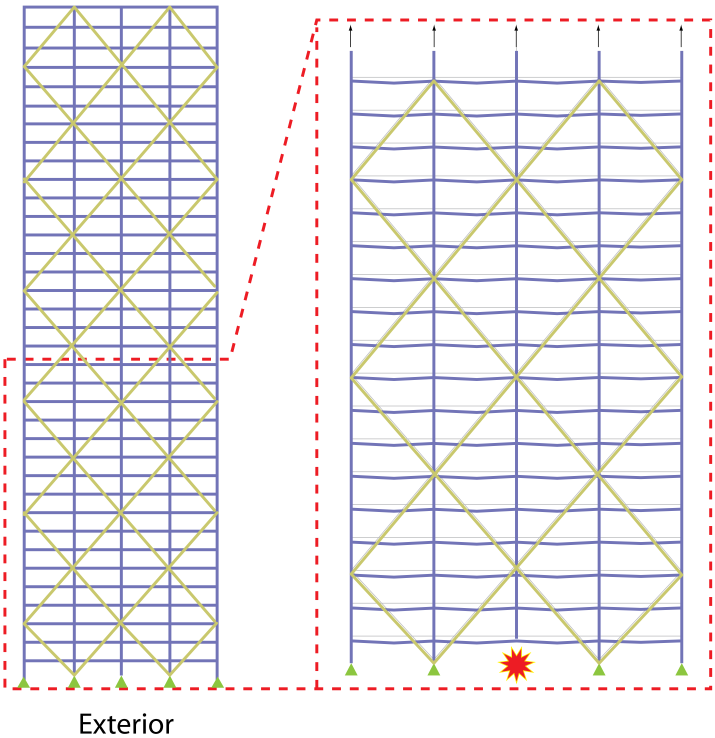
Figure 2: Tube Within Tube & Structural Response for Loss of Perimeter Column.

Description of Progressive Collapse

Progressive collapse occurs when the sudden loss of a critical load-bearing element initiates a chain reaction of structural element failures. Although this article focuses on the loss of a column due to an air-blast event, the cause of the initiating damage to the primary load-bearing element is unimportant. Once the critical load-bearing element is lost, the resulting sudden changes to the building's geometry and load-path are what contribute to instability and eventual partial or full collapse of the structure. The ability of each structural system to redistribute and support its gravity loads after loss of a perimeter column at ground level is examined below.

Structural Systems with Exterior Moment Frames

In exterior moment frame systems, resistance to progressive collapse is achieved by energy dissipation through formation of plastic hinges. Plastic hinges are developed as a result of large flexural deformations of beams and columns, which are directly correlated with the severity of the damage to both the building's structural and nonstructural elements.



Interior Core with Exterior Multistory Truss & Structural Response for Loss of Perimeter Column.

Type 1: Moment Frame with Core

A schematic plan and elevation of a typical moment frame with core system is provided in *Figure 1*. The building structural system consists of a regular grid of columns that are interconnected with beams. Moment connections between columns and beams are generally located along the building's perimeter to create an exterior moment frame that acts as the building's lateral resisting system. Gravity loads are taken by both the interior core and exterior moment frames.

If the building system were to lose a perimeter column, beams directly above would be forced to act as transfer girders, spanning between the two adjacent column lines, as shown in *Figure 2*. As the gravity loads are redistributed down the structure and to adjacent bays, the beams will eventually reach their plastic bending capacity and begin a formation of the first plastic hinge. If equilibrium is not satisfied through the redistribution of loads, the structure will continue to deform and plastic hinges will propagate along the column line and at the adjacent gridlines; however, structural collapse is not expected. Localized damage in the surrounding areas can be expected, as well as significant damage to architectural elements such as any partition walls, floor finishes, curtainwalls and exterior façade systems at upper floor levels due to the large vertical deformations of structural elements.

Type 2: Tube within Tube or Bundled Core

The structural layout of this building type is similar to Type 1; however, due to reduced column spacing and increased amount of moment connections, the structural system has an increased stiffness and overall redundancy. Under a lateral load, the peripheral frame will act similar to a tube with tension and compression stresses at the front and back frames respectively. Shear forces are resisted by the frames on either side.

If the building system were to lose a perimeter column, its response will be similar to Type 1. Hinges will first develop in beams and propagate to adjacent bays and column lines; however, damage will be contained to a smaller area of the building.

Structural Systems Without Exterior Moment Frames

Systems without exterior moment frames provide resistance to progressive collapse not through flexural deformation, as with the building types described above, but rather through development of tension in its structural members. Vertical large deformations are not expected, reducing the amount of overall building damage.

Type 3: Interior Core with Exterior Multi-story Truss

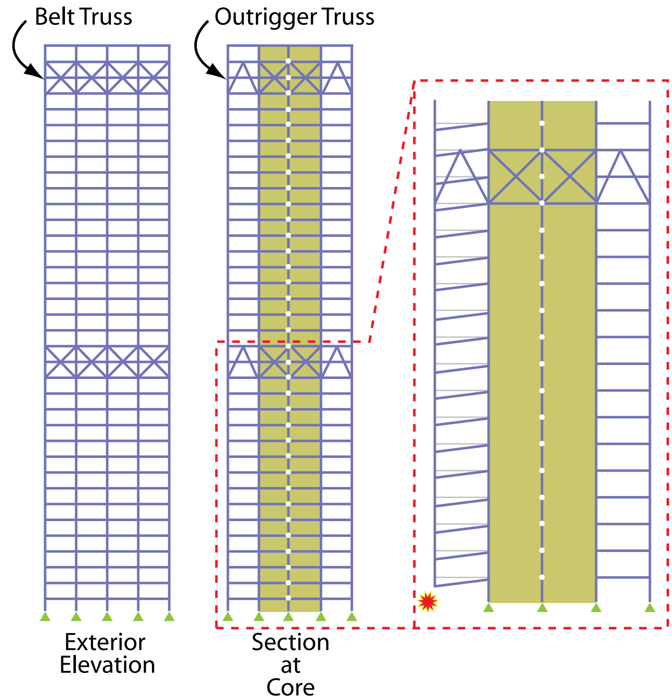
A common structural system in high rise buildings combines an interior core with an exterior braced frame that spans multiple floors. Lateral forces are taken by the exterior brace frame and the interior core. Gravity forces are taken by the exterior columns and the interior core.

If the building system were to lose a perimeter column, braces framing into the same column line that were initially unloaded will experience tension. Columns above the column-brace connection are now supported in compression by the upward vertical force component in the braces. The columns between the failed column and the supporting braces are tensioned. Columns were designed for larger compression loads; therefore, they are able to hold the tension as long as the column to column lap splices have sufficient tension capacity. The load in the brace travels to the adjacent bays, loading the vertical members. The additional force brings the columns closer to the limiting critical buckling load.

Type 4: Core with Outrigger Trusses

This system consists of a central core with multiple outrigger levels at which peripheral belt trusses interconnect exterior columns. The outrigger and belt trusses are generally large, stiff members that can extend vertically between two story heights. The perimeter beams are not necessarily required to be moment-connected to the columns.

Once a perimeter column is lost, the load will redistribute itself upwards along the column line, assuming adequate detailing of tension lap splices have been provided. As the redistributed forces reach the belt truss and outrigger level, a portion of the load will transfer through the belt truss to adjacent columns. Additionally, the outriggers will transfer some load into the core of the structure. Although the core is typically designed for low axial stresses due to ductility requirements in resisting overturning moments, the increase in stress due to the load transfer is expected to be minimal. Exterior columns at the opposite side of the building will also become engaged in tension, and will act with the core and to rebalance the structure. Similar to Type 3, non-structural damage will be moderate since deformations due to elongation of columns and bending in belt and outrigger trusses are expected to be minimal.



Interior Core with Outrigger Truss & Structural Response for Loss of Perimeter Column.

Type 5: Core Only

This type of building is similar to the Type 4 where the central core reacts for lateral loads and behaves as a cantilever. The link beams above the core door openings are used as a damping system during the seismic event. The floor gravity system is generally a flat slab, reinforced concrete or post tensioning concrete, without any beam. The slab connects directly to the column.

Once the perimeter column is lost, the system deforms similarly to Type 1. The difference is that the flat slab's moment capacity is minimal for this load's magnitude; system failure is expected. The punching shear at the slab to column connection is an additional phenomena expected to happen, especially for these large deformations and rotations. Type 5 structures should fail since an alternative redundant and ductile force path is missing.

Structural redundancy and robust connections are essential factors for resisting progressive collapse, regardless of structural system type. However, as described above certain lateral systems can provide improved performance against progressive collapse by limiting the propagation of damage throughout the building through development of tension in members rather than bending. These systems, such as Type 3 and 4 can even provide the possibility of remaining in the elastic range during the entire event, significantly limiting the level of deformation and damage throughout the building.▪

Vincenzo Melchiorre, P.E. is a Senior Engineer at Hinman Consulting Engineers in San Francisco. He has participated in a variety of projects both within the United States and internationally, including analysis and design of high rise buildings, design of blast resistant structures, seismic peer reviews, and progressive collapse analysis. He can be reached at ***vincenzo@hce.com****.*