Inferno at the World Trade Center, NY

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9-11: The fateful date

As in the morning hours of September 11, 2001 I was anxiously watching on TV the dramatic events taking place in New York City, and saw the two World Trade Center towers engulfed in immense flames brought about by terrorists who deliberately crashed two passenger jets into them, my training in Structural Engineering instantly elicited in me visions of doom, and a feeling that the towers were in imminent danger of collapse. Still, knowing that half a decade earlier the towers had resisted massive damage in a terrorist attack, and being unaware of similar cases of skyscraper collapse, I hoped against reason that they might survive yet again. To my horror, I then witnessed the unthinkable unfolding in front of my eyes. In retrospect, I should have been 100% sure that they would fail, but the idea was so disgusting that I allowed my wishful thinking to prevail instead. Soon after the tragedy occurred, cooler thoughts and the engineer in me returned, and I began to ponder about the mechanics that led to the catastrophe.

Why did they collapse?

From an engineering point of view, there were three causes to the massive structural damage that led to ultimate failure. These are the impact of the aircraft, the subsequent fireball, and most importantly, the raging fire caused by the vast amounts of jet fuel carried by the planes. Burning fuel must have also cascaded down floor openings to the levels below.

It has been reported that the towers were designed for the impact of a Boeing 707 aircraft then flying the skies. Considering that one of the towers survived for at nearly an hour, and the other almost two hours before collapsing, this demonstrated crash resistance provides compelling validation to this claim. It has also been opined by some that the towers did ultimately fail because the 767 is a far bigger jet carrying much more fuel than the design 707 aircraft. This view is largely incorrect. The takeoff weight of a fully loaded Boeing 707-320 is 151 tons (336,000 lbs.), and it carries a fuel load of 87,000 liters (23,000 gallons) of jet fuel. By contrast, the maximum takeoff weight of a Boeing 767-200 is some 178 tons (395,000 lbs.), and carries a fuel load of 91,000 liters (24,000 gallons). Assuming that jet fuel weighs like kerosene, this represents some 74 tons (164,000 lbs.) of fuel, or about half the weight of a fully loaded aircraft. Thus, while the 767 is indeed a somewhat larger aircraft, it is not significantly so, while its amount of fuel load is nearly the same as in the 707. In addition, both ill-fated planes were only lightly loaded with passengers, and their fuel tanks at the moment of impact have been estimated to be no more than 50% full. Hence, these planes did not carry their full takeoff load, but weighed instead no more than some 136 tons each. Thus, the buildings may indeed have been designed for the impact load caused by a commercial airliner the size of a Boeing 767, lost in fog in its approach to Kennedy Airport at landing speeds and with a modest fuel load remaining in its tanks. However, the designers never imagined a terrorist act during which high speed planes carrying large amounts of fuel would be deliberately crashed onto the towers, causing massive initial damage and triggering uncontrollable infernos.

From information publicly available, it is known that the weight of each building was carried by an inner core of columns surrounding elevator shafts and stairways, and by a dense lattice of external columns spaced 99cm (39 inches) on center forming an outer tube intended principally to prevent the building from overturning when subjected to strong lateral forces, such as those elicited by hurricane winds. The floors where supported by a grid of truss beams that carried the weight of the floors to the columns, while the floors in turn provided lateral support that prevented buckling of the columns.

The North Tower was hit at 8:46 above the 96th floor by a Boeing 767-200 flying at 691 km/hr (429 mph), and remained erect until 10:28, that is, nearly two hours after initial impact. By contrast, the South Tower was hit at 9:03 above the 80th floor by another 767-200 flying at 810 km/hr (503 mph) and collapsed less than an hour later at 9:59. The damage to the latter was more severe, perhaps because the second plane traversed the building at an angle and blew off external columns on two adjacent faces. This asymmetry, combined with the greater weight of the 31 stories above the crash elevation led to some tilting of the upper portion down the damaged corner, causing large overturning forces in the remaining members of the floor.

The initial impact of the aircraft caused massive structural damage to the external columns, to the floors in the proximity of the impact, and to the inner core. The ensuing fireball must have exacerbated significantly this damage, possibly collapsing locally several floors, and setting the buildings ablaze in a virtually uncontrollable, fierce fire. Still, both buildings survived this initial assault, and did not give way for a remarkably long period of time after the crash. This extraordinary capability allowed many lives to be saved, and is a major credit to the designers. Ultimately, however, the intense fire heated the structural steel elements well beyond the thermal limit of some 400°C (750°F), which caused the steel to lose both its stiffness and resistance, and as supporting members gave way, the final failure of the building was initiated.

Various mechanisms may have been at play in this failure. Witnesses who escaped the buildings in time reported seeing large cracks develop on the (non-structural) walls of the staircases. This suggests a steady redistribution of vertical forces and propagation of structural failure down the building. However, the immediate failure mechanism was almost certainly initiated locally at the elevation of the crash. Truss beams heated by the fire were probably more vulnerable than columns, and may have been the first to go. As parts of the floors then collapsed and rained down onto the floors below, the weight of the accumulating debris steadily increased beyond the support capacity of those floors, and they collapsed in turn. At the same time, local collapse of the floors caused the heat-weakened columns to loose their lateral support, which under the intense weight of the floors above the level of the fire caused them to buckle, break and roll out like matchsticks. At that point, the upper floors began to fall wholesale onto the structure below, and as they gained momentum, their crushing descent became unstoppable. Indeed, with two fairly simple dynamic models I developed in the hours following the collapse, I determined that the fall of the upper building portion down the height of a single floor must have caused dynamic forces exceeding the design loads by at least an order of magnitude (i.e. more than 10 times the weight of the upper floors). Thus, there was no way in the world that the columns below could have taken this large overload, and as these gave way, an avalanche down the building ensued causing the 110 story towers to collapse in about 12 seconds in what was practically a free fall. As reported by witnesses, the crushing of one floor onto one another caused a ratchet-like noise, whose frequency can be estimated to have been around 9 Hz (=110/12).

Earthquake in New York

The enormous mass of the twin towers, by virtue of its height above the ground, contained a substantial amount of gravitational energy, which could be likened to the energy of the water rising behind the dam of a hydroelectric power plant. Straightforward calculations indicate that for each tower, this energy was on the order of 10^{19} erg, or about 1% of the energy released by a 1 kiloton nuclear weapon. By comparison, the Hiroshima bomb was about 20 kilotons strong. While the towers were crashing to the ground, this energy converted into kinetic (or motion) energy, part of which was consumed as heat of collision, deformation and destruction of the structural materials. Back of the envelope calculations indicate, however, that a good fraction of the kinetic energy must have been conserved and transferred to the ground underneath, some of it dissipating as heat near the foundation, and the rest being converted into seismic waves that radiated into the surroundings. These waves shook the nearby buildings and generated small earthquakes in New York City that were recorded 34 km away at the Lamont-Doherty Earth Observatory, and were estimated to have possessed a magnitude of about 2.3 on the Richter scale. Back-calculations from this seismic intensity to total seismic energy at the source point demonstrate in turn that the energy carried by the seismic waves was only a very small fraction (less than 0.1%) of the kinetic energy released by the crash of the towers. Where did the remainder of the kinetic energy go? Probably, a good fraction may have gone straight down into the earth as body waves that did not radiate laterally near the surface to cause measurable vibrations. Thus, the characteristics of the seismic motions caused by a falling building may not be entirely analogous to the vibrations caused by seismic fault fractures familiar to seismologists.

Why did they not fall like a tree?

Some observers have wondered why the buildings telescoped down, instead of overturning and rolling to their side like a tree. However, buildings such as the WTC towers are not like trees. For one thing, they are not solid, rigid structures, but for the most part are open space (offices, staircases, elevator shafts, etc.). Indeed, a typical building is 90% air, and only 10% solid material. Thus, it is not surprising that a 110 story structure should have collapsed into 11 stories of rubble (actually less, because the rubble spreads out laterally, and parts are compressed into the foundation). In addition, the towers did not fail from the bottom up, but from the top down instead. For a portion of the tower to roll to either side, it must first acquire angular momentum, which can only occur if the structure can pivot long enough about a stable plane (e.g. the stump in a tree). However, the forces concentrated near the pivoting area would have been so large that the columns and beams in the vicinity of that area would simply have crushed and offered no serious support permitting rolling. Also, both building sections above the crash site were not tall enough to significantly activate an inverted pendulum effect. Thus, the upper part could do nothing but simply fall down onto the lower part, thereby crushing it from the top down. While videos of the collapse of the South Tower shows the upper part inclining just as it began to collapse, it did not fully roll to the side, but instead fell down onto the lower floors in a tilted position. There is also indirect evidence that the vertical resistance to telescoping or pancaking of either tower was minimal: the duration of the collapses of some 12 seconds was nearly the same as that of an object in free fall, while any serious resistance would have slowed down the collapse. Indeed, it takes an object falling freely from a height of 411 m (1350 ft) —the height of the towers— some 9 seconds to reach the ground. In essence then, the towers did not collapse like trees because the structures, despite their strength, were too fragile to sustain such motions.

Corollary to the WTC collapse

An important lesson to be learned from the WTC collapse is that buildings are like chains in the sense that these are only as strong as their weakest link. Hence, if the structural integrity of any floor in a building should be seriously endangered for some reason, such as a blast or a massive fire —perhaps excepting the very top floor or those immediately below it— , that building is in danger of collapsing and pancaking to the ground. However, inasmuch as catastrophic damage to all load bearing members is very rare and the vast majority of modern high rise buildings are well-engineered and designed to resist office fires —but not massive multi-story fires triggered by jet fuel and lost the sprinklers— these buildings are and will continue to be very safe indeed.

Can we design buildings to resist collapse? The answer to this question depends on what is meant by *design*. Sure, if we make *low* rise buildings as solid as the containment structures in nuclear power plants, it might be possible to design not only for impact and blast forces, but also for the massive fires caused by the jet fuel. But nobody would wish to live or work in such fortresses. In addition, they would be unbearably ugly. As for tall sky scrapers, it is virtually impossible to design a wall solid enough to resist penetration by a high speed plane while simultaneously providing open spaces for windows and carrying efficiently the weight of the crash barriers to the ground.

Then again, from a practical viewpoint, the chance that any *individual* building out of hundreds of thousands in the United States might suffer an attack is so small that it would not make economic sense to attempt making them jet-crash proof —and this chance should not be confused with the probability that *some* building in the US may be hit this way. As for retrofitting existing buildings, my view is that making them jet-crash proof would make no sense whatsoever. However, it would make eminent sense to retrofit at least some buildings, perhaps as part of an overall escape system overhaul, to ensure that load bearing elements have sufficient thermal protection and the buildings can survive a fierce fire for several hours. By providing adequate redundancies in the form of both alternative egress routes and sufficient escape time, we can prevent deadly consequences to people even when we should not able to avoid ultimate structural collapse. These improvements may be needed if for no other reason than to allay the concerns of people whose fear of a similar tragedy will persist for years to come. I, for one, would not wish to live or work in a mouse trap with insufficient escape paths.