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Inferno at the World Trade Center, NY

As in the morning hours of Sept. 11 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 explosion, 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 appears to validate this claim. It has also been opined by some, among them the building's architect, 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 336,000 lbs., and it carries a fuel load of 23,000 gallons of jet fuel. By contrast, the maximum takeoff weight of a Boeing 767-200 is some 395,000 lbs., and carries a fuel load of 24,000 gallons. (If jet fuel weighs like kerosene, this would represent some 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, so they did not carry their full takeoff weight. The implication is that the buildings may indeed have been designed for the impact load caused by a commercial airliner, but the designers never considered the fuel load and inferno that would surely ensue. Thus, the suggestion that the buildings were designed for the crash of an aircraft is ultimately self-delusion —and perhaps also public relations— on the part of the design team, because not all aspects of a crash, i.e. the explosion and fire, were taken into account, perhaps because the probability of such an occurrence was deemed insignificant.

From information available on the web, it appears that the weight of each building was mainly carried by an inner core of columns surrounding elevator shafts and stairways, while a dense lattice of external columns spaced 39 inches on center formed 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 inner core, 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, 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 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 perhaps also to parts of the inner core. The ensuing explosion 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 800 F, which caused the steel to lose resistance or even melt, 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 walls of the staircases. This would suggest 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 caused them to buckle and collapse under the intense weight of the floors above the level of the fire. 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 failed in turn and collapsed, a domino-effect down the building ensued. The towers then collapsed in what was practically a free fall.

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 collapse 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 photographic evidence shows the upper part of the South Tower to be inclined just as it began to collapse, it may not necessarily have rolled to the side, but instead fallen down onto the lower floors in a tilted position. (A careful review of collapse videos and additional photos should help clarify this contention). There is also indirect evidence that the vertical resistance to telescoping or pancaking of either tower was minimal: the duration of the collapses was nearly the same as that of an object in free fall, while any serious resistance would have slowed down the collapse. Some early reports (US News) have stated that the North Tower collapsed in 8 seconds, while the South Tower did so in 10 seconds. The former estimate is surely in error, because it takes an object falling freely from a height of 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 highly likely to collapse and pancake 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 jet fuel fires), 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 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. From a practical viewpoint, the chance that any *individual* building out of hundreds of thousands (millions?) in the nation might suffer an attack is so small that it would not make economic sense to make them jet-crash proof. (And do not confuse this chance 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 escape 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 other 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 routes.