Eduardo Kausel Professor of Civil & Environmental Engineering Massachusetts Institute of Technology September 2001

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 (see the appendix), 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.

APPENDIX: Two simple dynamic models explaining pancaking

Many observers have wondered why the WTC towers pancaked (or telescoped) to the ground in the course of their collapse. Using two admittedly crude, but simple dynamic models, we show here that once a damaged floor succumbs to the fire and causes the floors above the impact area to initiate their fall onto the floors underneath, it is not possible for the base of the building to stop the downward motion and the system collapses. Floors then crumble one after another in domino like fashion.

Model 1: Single degree of freedom system

Consider a model of the WTC buildings consisting of three sections, as shown in Fig. 1a, namely the upper floors, the lower floors, and a single damaged floor at the impact elevation. Let L and H be the heights of the block of floors above and below the damaged elevation, respectively, h the height of a single floor, and m the total mass of the upper part. Neglecting inertia effects in the lower part, we proceed to model it as a simple spring with vertical stiffness k.

Next, assume that the load bearing elements in the damaged floor fail and are no longer able to carry the weight of the upper part. At this point in time, the mass *m* falls down through the height *h* and impinges onto the top of the lower part with downward velocity $V = \sqrt{2gh}$. From this point on, and disregarding inelastic effects in the lower part —after all, we are a priori assuming that the structure may survive— we model the assembly as a single degree of freedom (SDOF) undergoing a dynamic displacement *u*. This system has initial conditions $u_0 = 0$ and $\dot{u}_0 = V$.

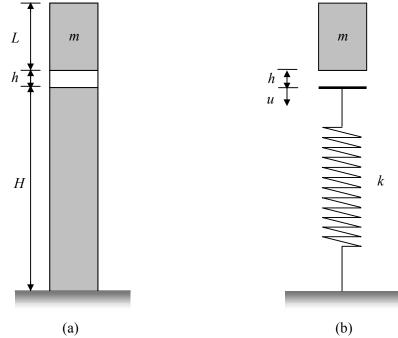


Figure 1 Modeling of WTC as (a) a column and (b) a SDOF system

The equation of motion for this simple SDOF system is

whose solution is

$$u = \left[\left(u_0 - \Delta \right) \cos \omega_n t + \frac{V}{\omega_n} \sin \omega_n t \right] + \Delta$$

in which $\omega_n = \sqrt{k/m}$ is the natural frequency of the system, $\Delta = mg/k$ is the static vertical deflection that would be caused by the weight of the upper floors in the absence of dynamic effects, and $V = \sqrt{2gh}$ is the initial velocity. Dividing by the static deflection, we obtain the dynamic load factor

$$\frac{u}{\Delta} = 1 + \left[-\cos\omega_n t + \sqrt{\frac{2ghm}{k\Delta^2}} \sin\omega_n t \right] = 1 + \sqrt{1^2 + \frac{2h}{\Delta}} \sin(\omega_n t - \varphi)$$

where we have used the fact that $k\Delta = mg$. Also, the exact expression for the phase angle φ is not needed here, because we are interested only in the maximum value, which is

$$\left(\frac{u}{\Delta}\right)_{\max} = 1 + \sqrt{1 + \frac{2h}{\Delta}}$$

Now, we don't really know Δ , but we can easily provide bounds to its value. Indeed, expressing Δ in terms of the vertical strain ε , we obtain

$$\left(\frac{u}{\Delta}\right)_{\max} = 1 + \sqrt{1 + 2\frac{h}{H}\frac{1}{\epsilon}}$$

On the other hand, we know that the vertical strain ε must be less than the yield strain of the support columns, because otherwise these columns would not have been able to carry the weight of the upper floors under normal conditions. For many materials, such as steel and concrete, this yield strain is of the order of $0.001=10^{-3}$. After taking into consideration safety factors, the prevention of buckling in its various forms, and the fact that the columns represented by *k* must have been able to carry not only the weight of the upper floors, but also the weight of the lower floors, the strain ε is likely to have been less than 10^{-4} . Using this upper bound in the expression above, and considering that H/h=80 is the number of floors below the damaged area, we obtain

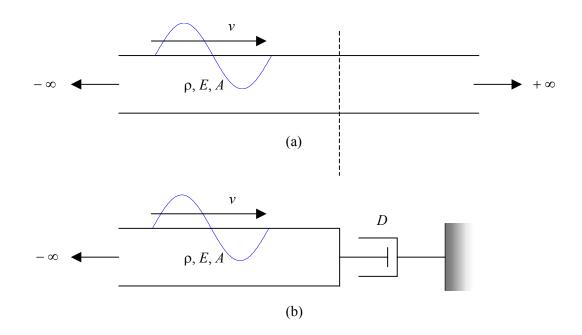
$$\left(\frac{u}{\Delta}\right)_{\max} = 1 + \sqrt{1 + 2\frac{1}{80}\frac{1}{10^{-4}}} \approx 17$$

This tentative (admittedly crude) value shows that the dynamic stresses are at least an order of magnitude larger than the static stresses. This is in fact so large that the columns in the floors below could not possibly have sustained them.

Model 2: Wave propagation problem (an infinite rod)

In our first model, we neglected the inertia of the floors below the damaged area, which undoubtedly offers resistance to the downward motion of the upper block. For this reason, we consider next an alternative model that considers a shock wave propagating downward the building in the instants following the collapse of the upper floors. To this effect, we model the towers as rods that can sustain axial wave propagation.

Clearly, when a rod is subjected to dynamic forces at one end, waves are elicited that propagate along the rod. In the instants preceding the reflection of these waves at the opposite end of the rod (i.e. the bottom of the buildings), the presence of that boundary has no effect on the wave motion, and the rod can be idealized as being infinitely long. Such infinite rod can in turn be shown to behave like an ideal viscous dashpot (damper) with a constant $D = \rho CA$, in which ρ is the mass density, $C = \sqrt{E/\rho}$ is the rod wave velocity, A is the cross-section of the rod, and E is the Young's modulus. The force-velocity relationship for that dashpot is then



$$P = D\dot{u} = \rho CAV$$

Figure 2: (a) Waves in an infinite rod, and (b) semi-infinite rod / dash-pot equivalent

Let's apply this model to the WTC collapse problem. The force *P* represents the dynamic force exerted onto the lower part by the upper part falling with velocity $V = \sqrt{2gh}$. For ρ , *C*, and *A*, we must consider the average building density ρ_{av} and the average (or equivalent) Young's modulus E_{av} , which is obtained as

$$E_{av} = \frac{E_c A_c}{A}$$

with A_c being the total cross-section area of all columns, E_c is the Young's modulus of each column, and A is the total cross-section of the building. The dynamic force is then

$$P = DV = \rho_{av}CA\sqrt{2gh} = \rho_{av}A\sqrt{\frac{E_cA_c}{\rho_{av}A}}\sqrt{2gh} = \sqrt{2gh\rho_{av}E_cA_cA}$$

which leads to a dynamic amplification factor

$$\frac{P}{mg} = \frac{\sqrt{2gh\rho_{av}E_cA_cA}}{\rho_{av}ALg} = \sqrt{2\frac{hE_cA_c}{\rho_{av}AL^2g}} = \sqrt{2\frac{hkH}{mgL}} = \sqrt{2\frac{hH}{\Delta L}}$$

that is

$$\frac{P_{dyn}}{P_{stat}} = \sqrt{2\frac{h}{\varepsilon L}}$$

Setting appropriate values $\varepsilon = 10^{-4}$ and h/L = 1/30 in this expression, we obtain

$$\frac{P_{dyn}}{P_{stat}} = \sqrt{2\frac{h}{\varepsilon L}} = \sqrt{2\frac{1}{10^{-4} \times 30}} \approx 26$$

This value, while larger than that of model 1, is of the same order of magnitude. Hence, these two crude models confirm that the dynamic forces exerted onto the lower floors by the fall of the upper floors vastly exceeds that elastic limit of the building, so that the collapse is unstoppable. Of course, both of these models are based on linear elastic material behavior, but the overload ratios thus found are so large that it seems certain that more refined, inelastic models would confirm the prediction of failure.