Why Did the World Trade Center Collapse? Science, Engineering, and Speculation

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There have been numerous reports detailing the cause of the World Trade Center Tower collapse on September 11, 2001. Most have provided qualitative explanations; however, simple quantitative analyses show that some common conclusions are incorrect; for example, the steel could not melt in these flames and there was more structural damage than merely softening of the steel at elevated temperatures. Some guidelines for improvements in future structures are presented.

INTRODUCTION

The collapse of the World Trade Center (WTC) towers on September 11, 2001, was as sudden as it was dramatic; the complete destruction of such massive buildings shocked nearly everyone. Immediately afterward and even today, there is widespread speculation that the buildings were structurally deficient, that the steel columns melted, or that the fire suppression equipment failed to operate. In order to separate the fact from the fiction, we have attempted to quantify various details of the collapse.

The major events include the following:

- The airplane impact with damage to the columns.
- The ensuing fire with loss of steel strength and distortion (Figure 1).
- The collapse, which generally occurred inward without significant tipping (Figure 2).

Each will be discussed separately, but initially it is useful to review the overall design of the towers.

THE DESIGN

The towers were designed and built in the mid-1960s through the early 1970s. They represented a new approach to skyscrapers in that they were to be very lightweight and involved modular construction methods in order to accelerate the schedule and to reduce the costs.

To a structural engineer, a skyscraper is modeled as a large cantilever vertical column. Each tower was 64 m square, standing 411 m above street level and 21 m below grade. This produces a height-to-width ratio of 6.8. The total weight of the structure was roughly 500,000 t, but wind load, rather than the gravity load, dominated the design. The building is a huge sail that must resist a 225 km/h hurricane. It was designed to resist a wind load of 2 kPa—a total of lateral load of 5,000 t.

In order to make each tower capable of withstanding this wind load, the architects selected a lightweight "perimeter tube" design consisting of 244 exterior columns of 36 cm square steel box section on 100 cm centers (see Figure 3). This permitted windows more than one-half meter wide. Inside this outer tube there was a 27 m × 40 m core, which was designed to support the weight of the tower. It also housed the elevators, the stairwells, and the mechanical risers and utilities. Web joists 80 cm tall connected the core to the perimeter at each story. Concrete slabs were poured over these joists to form the floors. In essence, the building is an egg-crate construction that is about 95 percent air, explaining why the rubble after the collapse was only a few stories high.

The egg-crate construction made a

redundant structure (i.e., if one or two columns were lost, the loads would shift into adjacent columns and the building would remain standing). Prior to the World Trade Center with its lightweight perimeter tube design, most tall buildings contained huge columns on 5 m centers and contained massive amounts of masonry carrying some of the structural load. The WTC was primarily a lightweight steel structure; however, its 244 perimeter columns made it “one of the most redundant and one of the most resilient” skyscrapers.[1]

THE AIRPLANE IMPACT

The early news reports noted how well the towers withstood the initial impact of the aircraft; however, when one recognizes that the buildings had more than 1,000 times the mass of the aircraft and had been designed to resist steady wind loads of 30 times the weight of the aircraft, this ability to withstand the initial impact is hardly surprising. Furthermore, since there was no significant wind on September 11, the outer perimeter columns were only stressed before the impact to around 1/3 of their 200 MPa design allowable.

The only individual metal component of the aircraft that is comparable in strength to the box perimeter columns of the WTC is the keel beam at the bottom of the aircraft fuselage. While the aircraft impact undoubtedly destroyed several columns in the WTC perimeter wall, the number of columns lost on the initial impact was not large and the loads were shifted to remaining columns in this highly redundant structure. Of equal or even greater significance during this initial impact was the explosion when 90,000 L gallons of jet fuel, comprising nearly 1/3 of the aircraft’s weight, ignited. The ensuing fire was clearly the principal cause of the collapse (Figure 4).

THE FIRE

The fire is the most misunderstood part of the WTC collapse. Even today, the media report (and many scientists believe) that the steel melted. It is argued that the jet fuel burns very hot, especially with so much fuel present. This is not true.

Part of the problem is that people (including engineers) often confuse temperature and heat. While they are related, they are not the same. Thermodynamically, the heat contained in a material is related to the temperature through the heat capacity and the density (or mass). Temperature is defined as an intensive property, meaning that it does not vary with the quantity of material, while the heat is an extensive property, which does vary with the amount of material. One way to distinguish the two is to note that if a second log is added to the fireplace, the temperature does not double; it stays roughly the same, but the size of the fire or the length of time the fire burns, or a combination of the two, doubles. Thus, the fact that there were 90,000 L of jet fuel on a few floors of the WTC does not mean that this was an unusually hot fire. The temperature of the fire at the WTC was not unusual, and it was most definitely not capable of melting steel.

In combustion science, there are three basic types of flames, namely, a jet burner, a pre-mixed flame, and a diffuse flame. A jet burner generally involves mixing the fuel and the oxidant in nearly stoichiometric proportions and igniting the mixture in a constant-volume chamber. Since the combustion products cannot expand in the constant-volume chamber, they exit the chamber as a very high velocity, fully combusted, jet. This is what occurs in a jet engine, and this is the flame type that generates the most intense heat.

In a pre-mixed flame, the same nearly stoichiometric mixture is ignited as it exits a nozzle, under constant pressure conditions. It does not attain the flame velocities of a jet burner. An oxyacetylene torch or a Bunsen burner is a premixed flame.

In a diffuse flame, the fuel and the oxidant are not mixed before ignition, but flow together in an uncontrolled manner and combust when the fuel/oxidant ratios reach values within the flammable range. A fireplace flame is a diffuse flame burning in air, as was the WTC fire. Diffuse flames generate the lowest heat intensities of the three flame types.

If the fuel and the oxidant start at ambient temperature, a maximum flame temperature can be defined. For carbon burning in pure oxygen, the maximum is 3,200°C; for hydrogen it is 2,750°C. Thus, for virtually any hydrocarbons, the maximum flame temperature, starting at ambient temperature and using pure oxygen, is approximately 3,000°C.

This maximum flame temperature is reduced by two thirds if air is used

Figure 1. Flames and debris exploded from the World Trade Center south tower immediately after the airplane’s impact. The black smoke indicates a fuel-rich fire (Getty Images).

Figure 2. As the heat of the fire intensified, the joints on the most severely burned floors gave way, causing the perimeter wall columns to bow outward and the floors above them to fall. The buildings collapsed within ten seconds, hitting bottom with an estimated speed of 200 km/h (Getty Images).

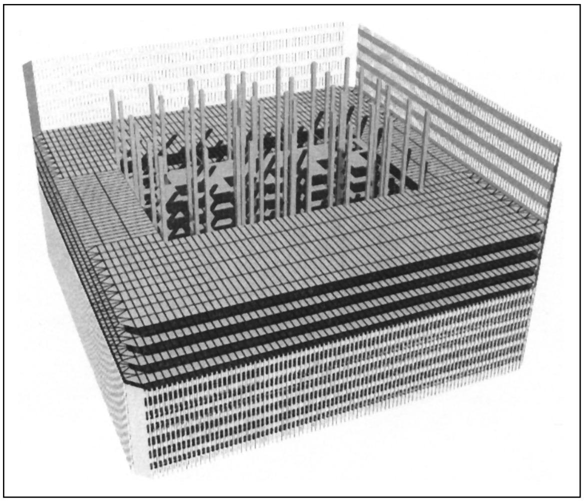

Figure 3. A cutaway view of WTC structure.

rather than pure oxygen. The reason is that every molecule of oxygen releases the heat of formation of a molecule of carbon monoxide and a molecule of water. If pure oxygen is used, this heat only needs to heat two molecules (carbon monoxide and water), while with air, these two molecules must be heated plus four molecules of nitrogen. Thus, burning hydrocarbons in air produces only one-third the temperature increase as burning in pure oxygen because three times as many molecules must be heated when air is used. The maximum flame temperature increase for burning hydrocarbons (jet fuel) in air is, thus, about 1,000°C—hardly sufficient to melt steel at 1,500°C.

But it is very difficult to reach this maximum temperature with a diffuse flame. There is nothing to ensure that the fuel and air in a diffuse flame are mixed in the best ratio. Typically, diffuse flames are fuel rich, meaning that the excess fuel molecules, which are unburned, must also be heated. It is known that most diffuse fires are fuel rich because blowing on a campfire or using a blacksmith's bellows increases the rate of combustion by adding more oxygen. This fuel-rich diffuse flame can drop the temperature by up to a factor of two again. This is why the temperatures in a residential fire are usually in the 500°C to 650°C range.[2,3]

It is known that the WTC fire was a fuel-rich, diffuse flame as evidenced by the copious black smoke. Soot is generated by incompletely burned fuel; hence, the WTC fire was fuel rich—hardly surprising with 90,000 L of jet fuel available. Factors such as flame volume and quantity of soot decrease the radiative heat loss in the fire, moving the temperature closer to the maximum of 1,000°C. However, it is highly unlikely that the steel at the WTC experienced temperatures above the 750–800°C range. All reports that the steel melted at 1,500°C are using imprecise terminology at best.

Some reports suggest that the aluminum from the aircraft ignited, creating very high temperatures. While it is possible to ignite aluminum under special conditions, such conditions are not commonly attained in a hydrocarbon-based diffuse flame. In addition, the flame would be white hot, like a giant sparkler. There was no evidence of such aluminum ignition, which would have been visible even through the dense soot.

It is known that structural steel begins to soften around 425°C and loses about half of its strength at 650°C.[4] This is why steel is stress relieved in this temperature range. But even a 50% loss of strength is still insufficient, by itself, to explain the WTC collapse. It was noted above that the wind load controlled the design allowables. The WTC, on this low-wind day, was likely not stressed more than a third of the design allowable, which is roughly one-fifth of the yield strength of the steel. Even with its strength halved, the steel could still support two to three times the stresses imposed by a 650°C fire.

The additional problem was distortion of the steel in the fire. The temperature of the fire was not uniform everywhere, and the temperature on the outside of the box columns was clearly lower than on the side facing the fire. The temperature along the 18 m long joists was certainly not uniform. Given the thermal expansion of steel, a 150°C temperature difference from one location to another will produce yield-level residual stresses. This produced distortions in the slender structural steel, which resulted in buckling failures. Thus, the failure of the steel was due to two factors: loss of strength due to the temperature of the fire, and loss of structural integrity due to distortion of the steel from the non-uniform temperatures in the fire.

THE COLLAPSE

Nearly every large building has redundant design that allows for loss of one primary structural member, such as a column. However, when multiple members fail, the shifting loads eventually overstress the adjacent members and the collapse occurs like a row of dominoes falling down.

The perimeter tube design of the WTC

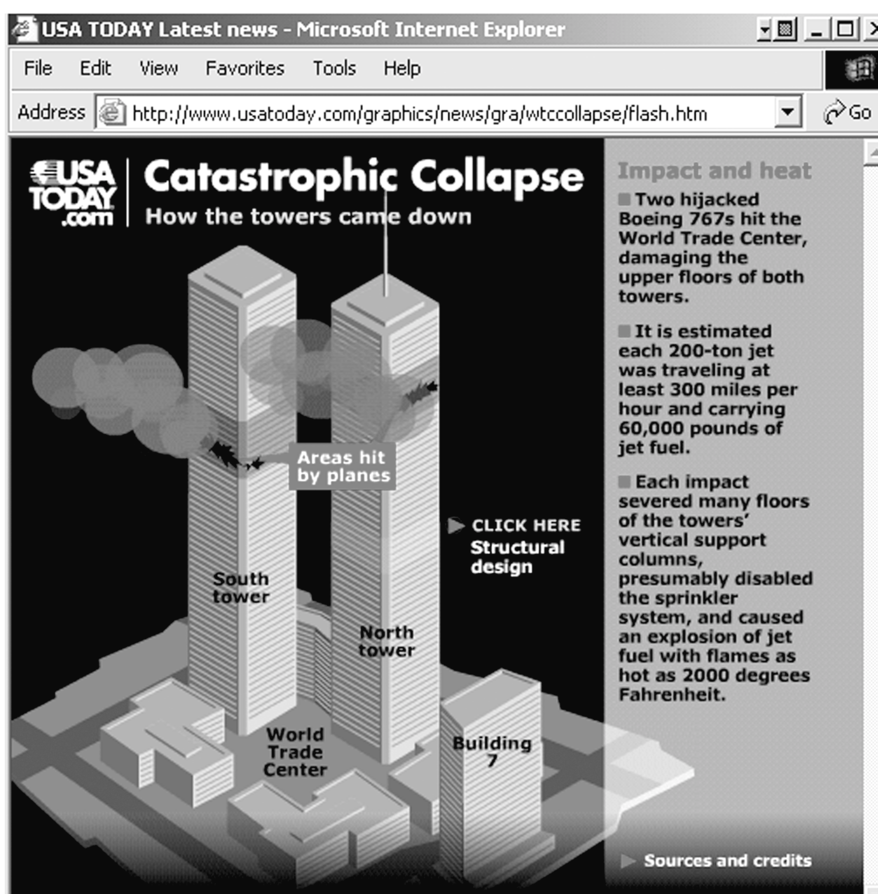

Figure 4. A graphic illustration, from the USA Today newspaper web site, of the World Trade Center points of impact.

was highly redundant. It survived the loss of several exterior columns due to aircraft impact, but the ensuing fire led to other steel failures. Many structural engineers believe that the weak points—the limiting factors on design allowables—were the angle clips that held the floor joists between the columns on the perimeter wall and the core structure (see Figure 5). With a 700 Pa floor design allowable, each floor should have been able to support approximately 1,300 t beyond its own weight. The total weight of each tower was about 500,000 t.

As the joists on one or two of the most heavily burned floors gave way and the outer box columns began to bow outward, the floors above them also fell. The floor below (with its 1,300 t design capacity) could not support the roughly 45,000 t of ten floors (or more) above crashing down on these angle clips. This started the domino effect that caused the buildings to collapse within ten seconds, hitting bottom with an estimated speed of 200 km per hour. If it had been free fall, with no restraint, the collapse would have only taken eight seconds and would have impacted at 300 km per hour.[1]

It has been suggested that it was fortunate that the WTC did not tip over onto other buildings surrounding the area. There are several points that should be made. First, the building is not solid; it is 95 percent air and, hence, can implode onto itself. Second, there is no lateral load, even the impact of a speeding aircraft, which is sufficient to move the center of gravity one hundred feet to the side such that it is not within the base footprint of the structure. Third, given the near free fall collapse, there was insufficient time for portions to attain significant lateral velocity. To summarize all of these points, a 500,000 t structure has too much inertia to fall in any direction other than nearly straight down.

WAS THE WTC DEFECTIVELY DESIGNED?

The World Trade Center was not defectively designed. No designer of the WTC anticipated, nor should have anticipated, a 90,000 L Molotov cocktail on one of the building floors. Skyscrapers are designed to support themselves for three hours in a fire even if the sprinkler system fails to operate. This time should be long enough to evacuate the occupants. The WTC towers lasted for one to two hours—less than the design life, but only because the fire fuel load was so large. No normal office fires would fill 4,000 square meters of floor space in the seconds in which the WTC fire developed. Usually, the fire would take up to an hour to spread so uniformly across the width and breadth of the building. This was a very large and rapidly progressing fire (very high heat but not unusually high temperature). Further information about the design of the WTC can be found on the World Wide Web.[5–8]

WHERE DO WE GO FROM HERE?

The clean-up of the World Trade Center will take many months. After all, 1,000,000 t of rubble will require 20,000 to 30,000 truckloads to haul away the material. The asbestos fire insulation makes the task hazardous for those working nearby. Interestingly, the approximately 300,000 t of steel is fully recyclable and represents only one day's production of the U.S. steel industry. Separation of the stone and concrete is a common matter for modern steel shredders. The land-filling of 700,000 t of concrete and stone rubble is more problematic. However, the volume is equivalent to six football fields, 6–9 m deep, so it is manageable.

There will undoubtedly be a number of changes in the building codes as a result of the WTC catastrophe. For example, emergency communication systems need to be upgraded to speed up the notice for evacuation and the safest paths of egress. Emergency illumination systems, separate from the normal building lighting, are already on the drawing boards as a result of lessons learned from the WTC bombing in 1993. There will certainly be better fire protection of structural members. Protection from smoke inhalation, energy-absorbing materials, and redundant means of egress will all be considered.

A basic engineering assessment of the design of the World Trade Center dispels many of the myths about its collapse. First, the perimeter tube design of the towers protected them from failing upon impact. The outer columns were engineered to stiffen the towers in heavy wind, and they protected the inner core, which held the gravity load. Removal of some of the outer columns alone could not bring the building down. Furthermore, because of the stiffness of the perimeter design, it was impossible for the aircraft impact to topple the building.

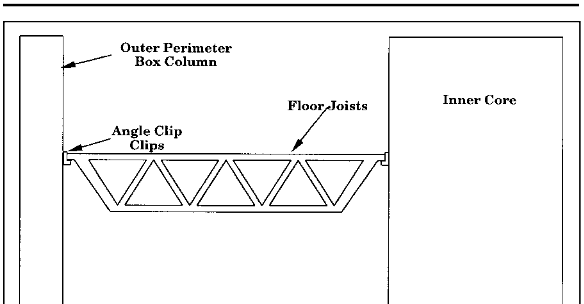

Figure 5. Unscaled schematic of WTC floor joints and attachment to columns.

However, the building was not able to withstand the intense heat of the jet fuel fire. While it was impossible for the fuel-rich, diffuse-flame fire to burn at a temperature high enough to melt the steel, its quick ignition and intense heat caused the steel to lose at least half its strength and to deform, causing buckling or crippling. This weakening and deformation caused a few floors to fall, while the weight of the stories above them crushed the floors below, initiating a domino collapse.

It would be impractical to design buildings to withstand the fuel load induced by a burning commercial airliner. Instead of saving the building, engineers and officials should focus on saving the lives of those inside by designing better safety and evacuation systems.

As scientists and engineers, we must not succumb to speculative thinking when a tragedy such as this occurs. Quantitative reasoning can help sort fact from fiction, and can help us learn from this unfortunate disaster. As Lord Kelvin said,

> "I often say . . . that when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely, in your thoughts, advanced to the stage of science, whatever the matter may be."

We will move forward from the WTC tragedy and we will engineer better and safer buildings in the future based, in part, on the lessons learned at the WTC. The reason the WTC collapse stirs our emotions so deeply is because it was an intentional attack on innocent people. It is easier to accept natural or unintentional tragedies; it is the intentional loss of life that makes us fear that some people have lost their humanity.

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