Destruction of the World Trade Center North Tower and Fundamental Physics

(Interpreted for a less technical audience)

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Running Title: Downward Acceleration of WTC 1

Abstract

The roof line of the North Tower of the World Trade Center is shown to have been in constant downward acceleration until it disappeared. A downward acceleration of the falling upper block implies a downward net force, which requires that the upward resistive force was less than the weight of the block. **[Newton's second law of motion says that a net force acting on a body will cause it to accelerate. The net force and the resulting acceleration will be in the same direction. In this case, since the measured acceleration is downward, the net force is also downward. Since the net force in this case is made up of gravity (acting downward) and structural resistance (acting upward), the upward resistance must be weaker than the gravitational force. However the gravitational force on the upper block is simply its weight, so we conclude that the resistive force is less than the weight**

of the upper block.] Therefore the downward force exerted by the falling block must also have been less than its weight. **[Newton's third law of motion says that forces come in pairs. Two bodies will always exert equal but opposite forces on each other. Therefore the downward force of the upper block on the lower section of the building is equal to the upward resistive force, which we have shown is less than the weight of the upper block.]** Since the lower section of the building was designed to support several times the weight of the upper block, the reduced force exerted by the falling block was insufficient to crush the lower section of the building. Therefore the falling block could not have acted as a "pile driver." The downward acceleration of the upper block can be understood as a consequence of, not the cause of, the disintegration of the lower section of the building.

Introduction

The destruction of the World Trade Center on September 11, 2001 was, by any assessment, a momentous turning point in world affairs. More than eight years after the event, the causes of the collapses of the three largest World Trade Center buildings (WTC 1, WTC 2, and WTC 7) remain hotly contested despite official reports by government agencies, first by FEMA then by NIST, attempting to lay the matter to rest. A "9/11 Truth Movement" has arisen, including over 1000 architects and engineers who are calling for a new investigation. The NIST investigators constructed an elaborate computer model of the buildings which they used to model the airplane crashes, but strangely they did not model the actual collapses of the Twin Towers. They took their analysis only up to the point of initiation of collapse, relying, as we shall see, upon a much more simplistic model proposed by Zdeněk Bazănt[4, 5, 6, 7], which concluded that once the collapse was initiated, total collapse was inevitable.

What follows here is an analysis that follows the simplifying assumptions laid out by Bazănt. Using measurements and a level of analysis accessible to an introductory physics class, undergraduate students have it within their power to evaluate the adequacy of the NIST-Bazănt model. Their physics background, even at this stage, equips them for intelligent participation in a significant civic debate.

The Pile Driver

The twin towers of the World Trade Center were destroyed in a top-down manner. More particularly, the section of the building from about the 98th floor upward to the roofline appeared to decouple and accelerate downward through the lower 98 floors. The mechanism of this process has been debated both among those limiting their search to a strictly natural explanation of the catastrophe (plane impacts, fire, and gravity) and among those willing to evaluate all possible explanations (including pre-planted explosives). The destruction of a building is a complex process, but simple physics applied to the observed motion of the roofline can constrain the choices among proposed theories. We will focus here on the details of the destruction of the North Tower. It was the first building to be hit by a plane and the second building to fall on September 11, 2001. It can be identified as the tower with the large antenna on its roof. The theory published by Thomas W. Eagar and Christopher Musso in JOM in December 2001,[1] and adopted by the Federal Emergency Management Agency (FEMA) study, postulated that the floor connections broke due to fire, leading to a "pancaking" collapse of the floors. This theory does not provide an explanation for why the core structure also failed, and it was rejected by the National Institute of Standards and Technology (NIST) study. Instead, the NIST report focuses on column failure. On the FAQ page of NIST's website we read:

NIST's findings do not support the "pancake theory" of collapse, which is premised on a progressive failure of the floor systems in the WTC towers. (The composite floor system, that connected the core columns and the perimeter columns, consisted of a crossed grid of steel trusses integrated with a concrete slab.) Instead, the NIST investigation concluded that the collapse was caused by sagging floor trusses pulling on the south wall perimeter columns causing them to bow inward and eventually fail. This mechanism requires that the floor trusses remain attached to the perimeter columns, so pancaking is ruled out.[2]

In NIST's view, fire caused a critical number of core and perimeter columns to weaken and eventually fail near the impact zone. The following is from p. 151 of their summary document, NIST NCSTAR 1.

Collapse Initiation

- The bowed south wall columns buckled and were unable to carry the gravity loads. Those loads shifted to the adjacent columns via the spandrels, but those columns quickly became overloaded as well. In rapid sequence, this instability spread all the way to the east and west walls.

- The section of the building above the impact zone (near the 98th floor), acting as a rigid block, tilted at least 8 degrees to the south.

- The downward movement of this structural block was more than the damaged structure could resist, and global collapse began. [3]

A series of papers by Zdeněk Bazănt,[4, 5, 6, 7] with various co-authors, describe what has become known as the "pile-driver" hypothesis, which appears to have been relied upon by the NIST investigation. Bazănt describes a scenario in which the top assembly of the building remains rigid as it crushes the lower sections of the building into rubble. Only when the lower section has been crushed into a compact debris pile does the top assembly crush itself. This proposed process has become known as "Crush-Down" followed by "Crush-Up." His claim is that once collapse is initiated, it becomes inevitable. Using Bazănt's analysis as a rationale, the NIST report limits its own investigation to the events leading up to the "initiation" of collapse, claiming that everything thereafter was inevitable and required no further investigation. NIST thereby sidesteps any consideration of what actually happened during the collapse itself, including evidence that might bring the correctness of Bazănt's analysis into doubt.

The Accelerating Destruction

The roofline of the North Tower appears to drop suddenly in what some observers loosely describe as "free fall" or "near free fall." To measure the actual motion of the roof line, a high quality copy of a video by Etienne Sauret (similar to a version available on YouTube[8]) was used. The Sauret video shows the North Tower's north face, which is identifiable by the presence of the aircraft impact hole. It is a particularly good video for our purposes because it shows a nearly level, nearly perpendicular view of the face of the tower taken from a distant stationary camera. A number of software packages allow the placement of markers frame-by-frame on a video clip for kinematic analysis. **[Kinematics is the study of motion.]** One such program is Tracker,[9] which is part of the Open Source Physics project.[10] The frame rate of the Sauret video clip, which is the standard NTSC rate of 30,000 frames per 1001 s, or approximately 29.97 fps, **[frames per second]** serves as the time base. The vertical scale was calibrated by the floor spacings which, apart from the sky lobby and the mechanical floors, are known to be 12 ft 0 in apart.[11] **[The calibration process converts the distances on the video, measured in pixels, to distances in the real world, measured in meters. A meter is 39.37 in, a little more than 3 ft.]** The vertical position of the roof line was marked every six frames (0.2 s intervals) and the data was exported to a spreadsheet for analysis. (See Table 1.)

Frame #	T (sec)	y (m)	v_y (m/s)
216	0.00	82.397	
222	0.20	82.399	0.010
228	0.40	82.401	0.010
234	0.60	82.403	-0.562
240	0.80	82.176	-1.708
246	1.00	81.720	-2.665
252	1.20	81.110	-3.400
258	1.40	80.360	-4.520
264	1.60	79.302	-5.860
270	1.80	78.016	-7.165
276	2.00	76.436	-8.485
282	2.20	74.622	-10.005

288	2.40	72.434	-11.505
294	2.60	70.020	-12.648
300	2.80	67.375	-13.968
306	3.00	64.433	-15.285
312	3.20	61.261	-16.240
318	3.40	57.937	-17.358
324	3.60	54.318	-18.300
330	3.80	50.617	-19.443
336	4.00	46.541	

Table 1: Video Measurement Data--Frame numbers indicate every 6th frame relative to the start of the video clip. The frame rate of the video is NTSC standard, 29.97 fps, yielding a measurement interval of 0.20 s. The y-values are the height of the roof line relative to an arbitrary origin. Velocities are computed by the symmetric difference differentiation algorithm.

A graph of the height of the roof line vs. time (Figure 1) displays the characteristic shape of a parabola indicating a downward acceleration. **[The graph in Figure 1 can be thought of as a picture of the height of the roofline spread out over time. The slope of this kind of graph gives the velocity. Note that the slope gets increasingly steep as it falls, indicating the building is picking up speed, or accelerating.]**

The vertical component of velocity was computed using a symmetric difference numerical differentiation algorithm,

$$v_n = \frac{y_{n+1} - y_{n-1}}{2\Delta t}\,. \tag{1}$$

[Velocity is similar to the ordinary concept of speed. To compute the speed, you would measure

the distance traveled divided by the time it took to travel that distance. To get the velocity for a particular time in the table by this method, we consider the prior position and the next position. Subtracting gives the distance traveled in two time intervals. We therefore divide by 2 times the time interval to get the velocity. This is a standard method for deriving velocity information from position data.] A graph of velocity vs. time (Figure 2) shows near uniformity of the downward acceleration from the 6th computed velocity point onward. When the roof line begins to fall, it quickly transitions to nearly uniform downward acceleration.

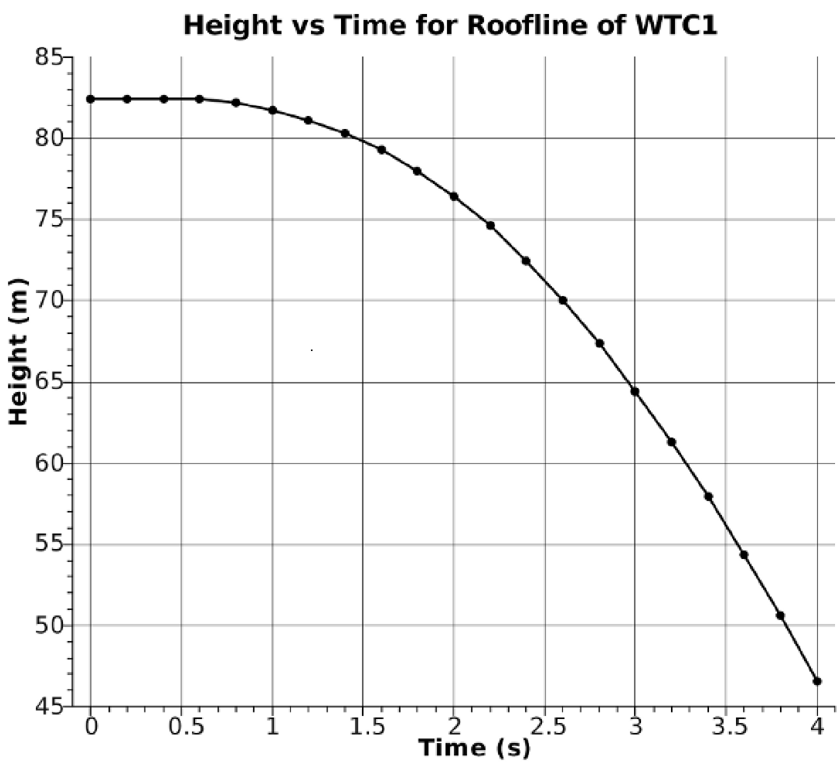

Figure 1: Graph of the height of the roof line (measured from an arbitrary origin) vs. time at 0.2 second intervals. Note that once it begins to fall the path appears approximately parabolic.

[If we graph the velocity vs. time, an object moving with constant acceleration will have a straight line graph. This is because its velocity increases by equal amounts in equal intervals of time. The slope of this kind of graph gives the acceleration, which is the rate of change of velocity. In this case the fact that the velocity vs. time graph is essentially a straight line indicates a constant downward acceleration.]

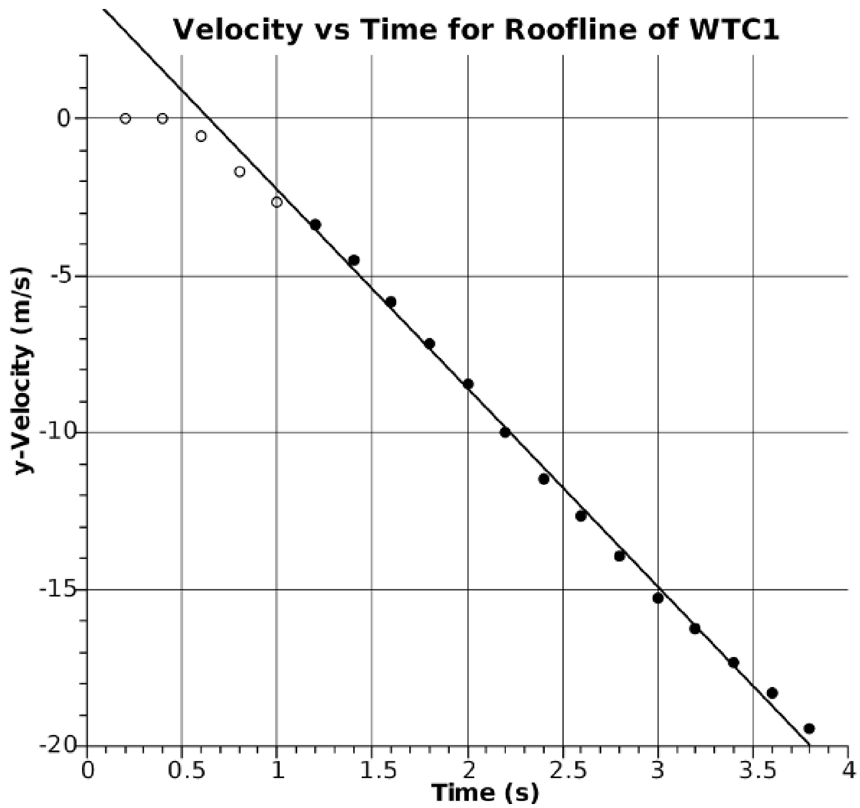

Figure 2: Velocity is here plotted as a function of time for the roof line of WTC1. The regression line **[i.e. the straight line that best fits the data]** is computed for the 6th computed velocity onward. The slope, in this context, is the acceleration: -6.31 m/s^2 with an R^2 value of 0.997. **[Since acceleration tells how many m/s the velocity increases each second, the unit of acceleration is (m/s) per s, abbreviated as m/s^2. The negative sign indicates downward acceleration. The R^2 value is a measure of how**

well the straight line fits the data; very well in this case.]

Observations

For the current analysis we follow Bazănt's simplifying assumptions [4, 5, 6, 7] by treating the upper section of the building as a solid block with mass m. The only two relevant forces acting on the falling block are gravity (*mg*) and an upward normal force (*N*) due to its interaction with the lower section of the building. **[“Normal” in a mathematical context indicates “perpendicular.” The forces between two surfaces perpendicular to the surfaces are called normal forces.]** Applying Newton's Second Law and solving for *N*, we get

$$mg - N = ma \qquad (2)$$

[Newton's second law can be written $F_{Net}=ma$. The gravitational and normal forces combine to form the net force on the left and the mass of the upper block and its acceleration are shown on the right.]

so

$$N = mg - ma \qquad (3)$$

[Turning Eq. 2 around algebraically we can determine the normal force: the force the lower section of the building exerts on the upper block.]

Our data shows that from the sixth computed velocity data point onward, the upper block is accelerating uniformly (with an R^2 value of 0.997) at a = -6.31 m/s^2, or in other words, 64% of the acceleration of gravity. For this value of *a*,

$$N = mg - 0.64mg = 0.36mg \quad (4)$$

Therefore the upward-acting normal force is 36% of the weight of the upper block, as illustrated in Figure 3. **[*mg* is the weight of the upper block. By plugging in the measured acceleration of the roofline we can see that the normal force is 0.36*mg*, or 36% of the weight of the upper block. We don't need to know the actual weight of the upper block to make this calculation.]**

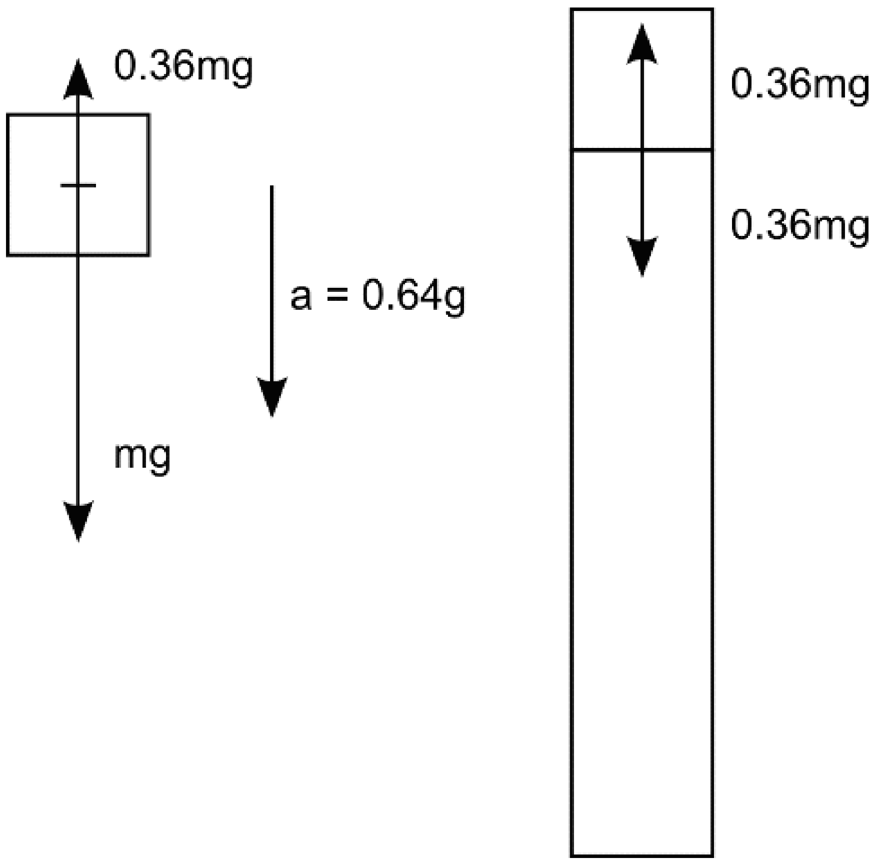

Figure 3: Consider the upper section of the building to be a block of weight mg. Since the acceleration of the block is measured to be downward at 0.64g, the net force acting on it must be 0.64mg. The gravitational force is mg, so the upward normal force must be 0.36mg. The upper and lower sections of the building exert equal but opposite forces on each other, so the load on the lower section of the building is 36% of the weight of the upper block.

Explicitly invoking Newton's Third Law puts this result in another light. **[Newton’s third law of motion says that forces come in pairs. Two bodies will always exert equal but opposite forces on each other.]** Since the forces in the interaction are equal and opposite, the falling block exerts a force of only 36% of its weight on the lower section of the building. In other words, as long as the falling block is accelerating downward we have the counter-intuitive result that the force it exerts on the lower section of the building is significantly less than its static weight. It is difficult to imagine how an upper block exerting a force of only 36% of its static weight could crush the larger, stronger, undamaged lower section of the building to the ground, when the building, at any level, was designed to support several times the weight above it. Assuming a safety factor of between 3 and 5 [12], the observed acceleration implies that close to 90% of the strength of the lower section of the building must have been eliminated by forces other than the supposed "pile driver," suggesting that some sort of controlled demolition was at work.

One might argue, in terms of the strength of the various elements, that the impact of the falling block might crush the lower section of the building (although this assertion has been challenged [13]), but it cannot crush the lower block while it maintains its downward acceleration. Prof. Graeme MacQueen and Tony Szamboti have made a parallel observation, based on a similar measurement, in their paper, "The Missing Jolt: A Simple Refutation of the NIST--Bazănt Collapse Hypothesis."[14] They point out that any increased force on the lower section of the building must be accompanied by a decrease in the momentum of the falling block. **[Momentum is mass times velocity, *mv*. The rate of change of momentum is mass times the rate of change of velocity, or in other words *ma*. Since Newton’s second law says *F=ma*, force can be thought of as a rate of change of momentum. If the falling block exerts a force on the lower block greater than its weight, the excess force must be coming from a transfer of momentum.]** The transfer of momentum (which implies a loss of momentum for the upper block) is what gives rise to the impulse. **[Impulse is the force times the time during which the force acts. It can be shown that the impulse is equal to the change in momentum.]** The falling block can lose momentum only to the extent that it decelerates. It should therefore experience a "jolt" **[a loss of speed; i.e. an upward acceleration]** which we should be able to see in the video analysis. But from the fact that the upper block continues to move downward without deceleration, it is clear that there was no jolt despite the significant deformation of the building in the first three seconds.

The fact that a downward accelerating block would exert a force less than its own weight on the target block may be difficult to accept intuitively, but that is because our experience suggests the target block would resist the crushing blow. A rapidly moving hammer head driving a nail into a solid block of wood typically exerts a force on the nail many times the weight of the hammer head. But that is true only if the nail resists the blow. The large force that drives the nail into the wood is matched by a force that simultaneously decelerates the hammer head, which is why multiple blows are typically required. If, however, the nail is placed on a block of Styrofoam it will not significantly resist the blow. It will be driven into the block with very little force. The falling hammer head will meet so little resistance that it will be able to accelerate the whole time. In the case of WTC1, the falling block acts like the hammer head driving the nail into Styrofoam, but, changing the picture a little, it is the interface between the two blocks that is "soft." Something other than the falling block (explosives?) must be destroying the structural integrity of the interface zone so that it offers only a small fraction of the resistance it was designed to provide.

Some might object to oversimplifying the model quite this much. It has been argued that the crushed material at the interface of destruction is accreted to the upper section so the mass of the falling block grows as it falls, producing an avalanche effect.[15] I would argue, from the fact that a major fraction of the mass landed outside the footprint of the building, that accretion was at most partial, but let us consider the effect of any such accretion. Newton's Second Law applied to a system of variable mass can be stated

$$F_{ext} + \left(\frac{dp}{dt}\right)_{accreted} = \left(\frac{dp}{dt}\right)_{system}, \tag{5}$$

where p is momentum and F_{ext} represents the net external force acting on the system.

[Think of a collection of objects surrounded by an imaginary boundary as a "system." The term on the right represents the rate of change of momentum of the system. This change can be brought about by external forces acting on the system or by new material coming into the system bring their own momentum with them.]

The accreted mass is initially at rest, so it brings no new momentum into the system:

$$\left(\frac{dp}{dt}\right)_{accreted} = 0. \tag{6}$$

[In the current situation the accreted material, the crushed building materials at the interface between the two sections of the building, is initially at rest, so it brings no new momentum into the system.]

Since $p = mv$ we can write, **[*p*, strange as it may seem, is the symbol for momentum]**

$$F_{ext} = \left(\frac{dp}{dt}\right)_{system} = \frac{d(mv)}{dt} = m\frac{dv}{dt} + v\frac{dm}{dt}. \tag{7}$$

[Here we are expanding the terms using the rules of calculus.]

In our situation (letting the downward direction be positive),

$$F_{ext} = mg - N \tag{8}$$

where N is the normal force, as in our earlier analysis. Recognizing $\frac{dv}{dt}$ as simply the acceleration, a,

[the rate of change of velocity is by definition the acceleration]

we can write

$$(mg - N) = ma + v\frac{dm}{dt}. \tag{9}$$

[Algebra: making some substitutions into Eq. 7]

Solving for N, we have

$$N = (mg - ma) - v\frac{dm}{dt}. \tag{10}$$

[More algebra]

Note that this is the same as our previous result (Eq. [3]) except the normal force is reduced even further, since both v and $\frac{dm}{dt}$ are positive.

[We are taking the downward direction to be positive. Since the velocity is in the positive (downward) direction and the mass is increasing, so the rate of change of mass is positive, the last term represents subtracting a positive number. Thus the normal force, taking accretion into account is even less than when accretion is ignored.]

Therefore, perhaps counter-intuitively, any accreted material reduces the effectiveness of an assumed pile driver. This result may become reasonably intuitive once one recognizes that the falling block must transfer some of its momentum to the accreted mass to bring it up to speed.

Summary

The fact that the roof line of the upper section of the North Tower continued to accelerate downward through the collision with the lower section of the building indicates that the upper section could not have been acting as a pile driver. As long as the roof line was accelerating downward, the upper block, exerted a force less than its own static weight on the lower section of the building. Any accretion of material into the upper block would have acted as an inertial brake, reducing the force of interaction even further. The undamaged lower section of the building was built to support several times the weight of the material above it, but whether or not we take the safety factor into account, the reduced force exerted by the falling mass could not have been what caused the violent destruction of the building seen in numerous videos. The persistent acceleration of the top section of the building is strong confirmation that some other source of energy was used to remove the structure below it, allowing the upper block to fall with little resistance.

Having assumed the existence of an indestructible falling block, with or without accretion, we have demonstrated that, given the observed acceleration, such a block could not possibly have destroyed the lower section of the building. When we turn to the video evidence we see that even the hypothesized existence of a persistent upper block is a fiction. Videos show that the section of the building above the plane impact point was the first section to disintegrate. It was significantly reduced in size prior to the onset of destruction of the lower section of the building. Once the roof line descends into the debris cloud there is no further evidence even of its continued existence. Whether or not it was completely destroyed early in the collapse is a moot point. We have shown that even if it continued to exist intact, it could not have played a significant role in the destruction of the building. A small section of a structure, consisting of a few floors, cannot one-way crush-down a significantly larger lower section of same structure by gravity alone.

Acknowledgments

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