A DISCUSSION OF THE FINAL NIST REPORT ON THE COLLAPSE OF WTC BUILDINGS 1 AND 2

By F. R. Greening

1.0 Introduction

The U.S. National Institute of Standards and Technology report: NIST NCSTAR 1 – 6, *Federal Building and Fire Safety Investigation of the World Trade Center Disaster*, issued in September 2005, provides a very detailed analysis of the collapse of WTC 1 & 2. The NIST report concludes, among other things, that WTC 1 & 2 collapsed by essentially the same mechanism involving the sagging and tilting of floor sections above the impact zones of each Tower. This led to the development of column instabilities in the exterior walls and the transfer of increasing gravity loads to critical core columns. These instabilities progressed rapidly along entire walls and induced a progressive collapse of the upper block of floors onto the floors below.

On page 320 of Chapter 9, we also read the following:

> "*NIST found no corroborating evidence for alternative hypotheses suggesting that the WTC towers were brought down by controlled demolition using explosives planted prior to September 11th, 2001. NIST also did not find any evidence that missiles were fired at or hit the towers.*"

Thus NIST are apparently quite satisfied that the initial aircraft impacts were sufficiently damaging to the WTC to lead to a self-sustaining global collapse of each Tower, a conclusion that is strongly contested by the 9-11 Truth Movement. It should first be noted that NIST's collapse theory is based almost entirely on conclusions drawn from computer modeling using very sophisticated finite element calculations. Most 9-11 "truth seekers", on the other hand, base their conclusion that explosives were used to bring down the Twin Towers on video and photographic evidence as well as eyewitness accounts by NYC police and firefighters. In the following pages we shall look at NIST's WTC collapse theory and endeavor to find out if it is supported by the facts…….

There should be no enmity among seekers of the truth
Aristotelis

2.0 An Analysis of the Key Findings of the NIST Final Report

The NIST report is certainly an impressive document containing over 10,000 pages of technical material on the WTC disaster. While there are many Sections and Chapters of interest to the present discussion we shall focus almost entirely on Chapters 8, 9 and 10, compiled by J. L. Gross et al; material that falls under the general heading: *Probable Collapse Sequence of the World Trade Center Towers*.

These Chapters of the NIST report review the critical events that were played out in a period of less than 2 hours at the World Trade Center on the morning of Sept 11th 2001:

- the aircraft impacts close to the 95th floor of the north wall for WTC 1 and the 80th floor of the south wall for WTC 2
- the subsequent fires , temperature rise and thermal expansion of truss seats
- the sagging of floors with associated floor/wall disconnections
- the inward bowing of exterior columns of the south wall for WTC 1 and the east wall for WTC 2.
- the tilting of the entire section of the building above the impact zone
- global collapse

On pages 300 and 308 of Chapter 9, the NIST report describes the key mechanistic process leading to the final global collapse of each tower in the following precise terms:

> **The change in potential energy due to the downward movement of building mass above the buckled columns exceeded the strain energy that could be absorbed by the structure. Global collapse then ensued**

The downward movements of the upper sections of the Twin Towers noted by NIST are the result of the asymmetric damage inflicted on the Towers by the aircraft impacts. The NIST report describes computer models that provide estimates of the downward displacements of the exterior walls and cores of the upper sections of WTC 1 & 2 after impact. These estimates are reported by NIST at various times *after* aircraft impact, but *before* collapse initiation, and are summarized in Table 1 below.

Table 1 : Downward Displacements (in cm) Calculated by NIST for WTC Upper Sections at Different Times After Impact

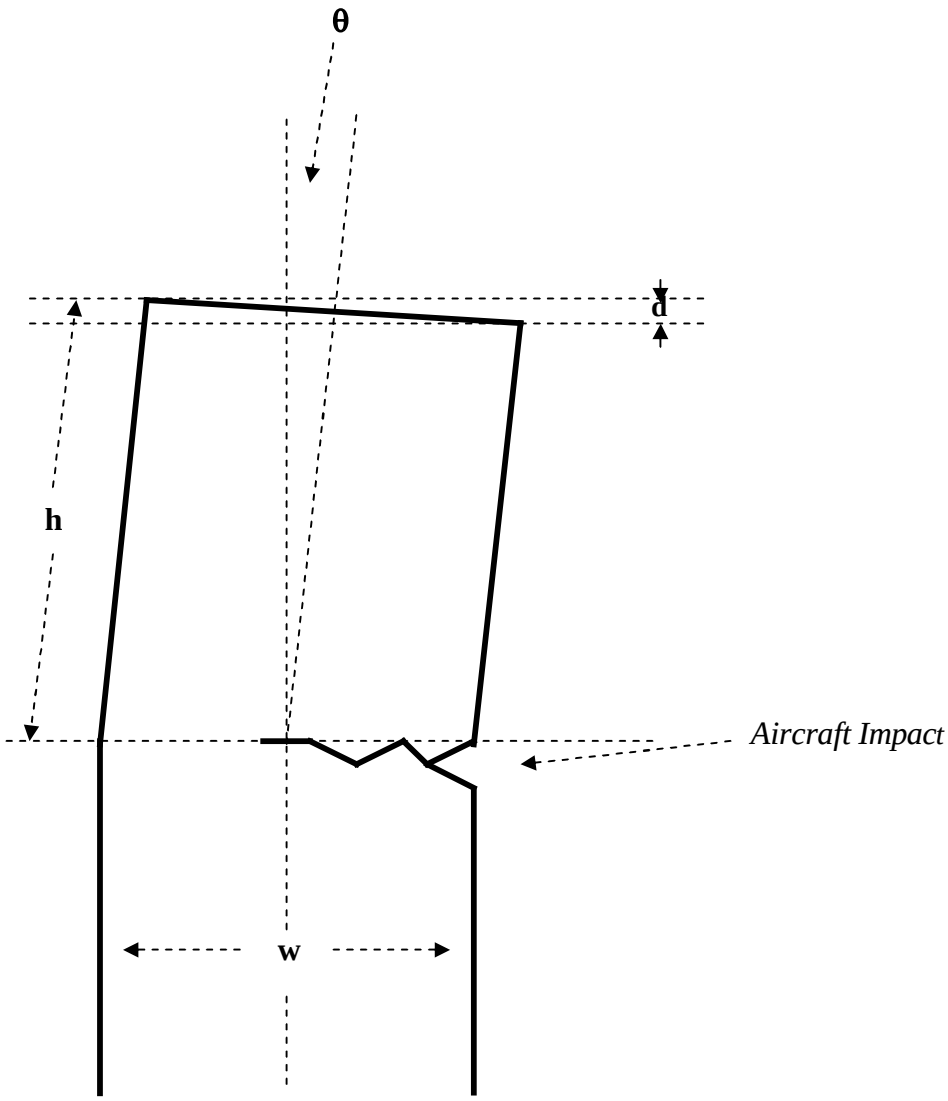
Time (min)	WTC1		WTC 2	
	Exterior Wall	Core	Exterior Wall	Core
43	-	-	28	33
100	10	9	-	-

N.B. WTC 2 collapsed after 56 minutes and WTC 1 after 102 minutes

As discussed by NIST, the displacements reported in Table 1 are not uniformly distributed across an entire floor but are localized on one or two sides of each Tower due to the nature of the impact damage and the subsequent tilting of the upper sections. Thus,

just prior to collapse, NIST estimate that WTC 1 was tilted down about 10 cm at its north face, while WTC 2 was tilted down about 30 cm at its southeast corner.

Some corroborating evidence for the magnitude of the downward displacements of the blocks of floors above the impact zones may be estimated from photographs or selected frames from videos of the Towers prior to their collapse. Below is a schematic of the geometry of a "Leaning Tower":



h is the height of the block (= the distance from the impact zone to the top of the Tower)
w is the width of the Tower
d is the maximum downward displacement of the block of floors
θ is the tilt angle

The geometry of the "Leaning Tower" requires that:

$$\mathbf{d = h\,[\,1 - \cos\theta\,] + w \sin\theta}$$

On page 308 of Chapter 9 of the NIST report we read in reference to the condition of WTC 2 just moments before it began to collapse:

"The entire section of the building above the impact zone began tilting as a rigid block (all four faces; not only the bowed and buckled east face) to the east (about 7° to 8°) and south (about 3° to 4°) as column instability progressed rapidly from the east wall along the adjacent north and south walls."

We have reviewed the available images of WTC 2 after the aircraft impact and would say that the maximum tilt of the upper section *prior to collapse initiation* was no more than about 2° from vertical; 8° is simply too large (as we will discuss later!).

Let's now calculate the expected downward displacement of WTC 2 for a 2° tilt angle: For WTC 2 the section above the impact zone is about 30 floors high. Hence **h**, the height of the section, is 30 floors × 3.7 meters per floor = 111 meters. Substituting $\boldsymbol{\theta = 2°}$ into our formula for **d**, the downward displacement of the block, we find:

$$\mathbf{d = 111 \times [\,1 - \cos 2°\,] + 64 \times \sin 2° = 2.3 \text{ meters or } 230 \text{ centimeters}}$$

This value is much larger than NIST's calculated values of 28 cm and 33 cm for the respective downward displacements of the core and exterior walls of the upper section of WTC 2 noted in Table 1 above. This discrepancy will be considered in detail below.

Energy Analysis:

In order to make use of the displacement data discussed above we return to NIST's key statement concerning the WTC collapse-initiating event, (p. 300 and 308 of Chapter 9)

> **The change in potential energy due to the downward movement of building mass above the buckled columns exceeded the strain energy that could be absorbed by the structure. Global collapse then ensued**

This statement may be expressed mathematically as:

Change in Potential energy = Absorbed strain energy

or, $$\mathbf{Mg\Delta d = E_s}$$

M is the building mass above the impact floor
g is the acceleration due to gravity
Δd is the downward displacement of the building mass
$\mathbf{E_s}$ is the absorbed strain energy

The above equation may also be written in its more familiar inverse form:

$$\mathbf{E_s = Mg\Delta d}$$

The NIST report suggests that the quantity **Δd**, the downward displacement in the upper section of each Tower, *increased at a rate ~ 5 – 15 cm/hr* ***after the aircraft impacts***. This slow downward sagging of floors in the impact zone over a period of less than two hours, meant that a portion of the enormous potential energy stored in each Tower was slowly, but inexorably, converted into strain energy $\mathbf{E_s}$. This strain energy eventually exceeded the elastic limit of the structural steel and produced irreversible deformations of support columns immediately below the impact zones – columns that had a finite capacity to absorb strain energy.

Observations of the first few seconds of the collapse of WTC 1 & 2 show that structural failure occurred in a sequential manner at every floor below the impact zone. Consideration of the conversion of potential energy into downward motion, first by reversible elastic yielding, then by irreversible column deformation, suggests the idea of a collapse-initiating energy, $\mathbf{E_c}$, equal to the *maximum* strain energy capacity $\mathbf{E_s(max)}$ of the support columns on a single floor.

We have previously modeled the WTC collapse in terms of a quantity we called $\mathbf{E_1}$, the *average* energy needed to collapse one WTC floor. Clearly $\mathbf{E_1}$ is equivalent to the collapse-initiating energy $\mathbf{E_c = E_s(max)}$. In our report *Energy Transfer in the WTC Collapse Events of September 11th 2001*, Section 4.2, a value of about 0.6 gigajoules (0.6×10^9 joules) was estimated for $\mathbf{E_1}$. We are now in a position to derive independent values of $\mathbf{E_1}$ using NIST's **Δd** data for WTC 1 and WTC 2. To do this we proceed as follows:

For WTC 1, with fourteen floors above the impact zone, we represent **M** by $\mathbf{M_{14}}$ and for WTC 2, with twenty-nine floors above the impact zone, we represent **M** by $\mathbf{M_{29}}$.

Since the mass of one Twin Tower is generally taken to be ~ 510,000,000 kg, we have:

$$\mathbf{M_{14} = 64{,}900{,}000\ kg}$$

$$\mathbf{M_{29} = 134{,}450{,}000\ kg}$$

Using NIST's values of **Δd**, namely 10 cm for WTC 1 and 30 cm for WTC 2, in the formula $\mathbf{E_s = E_1 = Mg\Delta h}$ (with g taken as 9.81 m/s^2), we find:

$$\mathbf{E_1(WTC\ 1) = 0.637 \times 10^8\ Joules} \quad \text{and} \quad \mathbf{E_1(WTC\ 2) = 3.96 \times 10^8\ Joules}$$

These values for E_1 are problematic because *E_1 should be essentially the same for each Tower*. In addition, as we intend to show, a more realistic value for **Δd** for WTC 2 based on a 1° tilt prior to collapse is ~ 1 meter, in which case $\mathbf{E_1(WTC\ 2) \approx 1.4 \times 10^9\ Joules}$.

3.0 Discussion

The NIST "Final Report" on the collapse of the World Trade Center considers the entire sequence of events from the initial aircraft impacts on WTC 1 & 2 to the first moments of the collapse of these buildings. While many factors probably played a role in the collapse sequence, NIST propose a relatively simple mechanism as the root cause of the collapse of the Towers: the development of structural instability in the floor areas around the aircraft impact zones – an instability made manifest by *a gradual downward displacement and tilting of the entire section of floors above the impact zone*.

The NIST collapse mechanism assumes that support structures in the impact zone were put into states of heightened tension or compression in response to the asymmetric impact damage to the Tower. The Towers remained relatively stable after impact, however, because the exterior wall and core columns were able to absorb strain energy to compensate for the downward displacements brought about by local floor collapse in the impact zone. Nevertheless, in the time interval between aircraft impact and total structural failure, the Towers developed instabilities that tended to *increase* the slumping, twisting and tilting of the sections above the impact zone. Global collapse ensued when the strain absorbing capacity of columns below the impact zone was exceeded. From a detailed analysis of the structural response of WTC 1 & 2 to the aircraft impacts, the NIST Report estimates the magnitude of the displacement and tilting of the upper section of each Tower *before collapse*. These displacements and tilts are generally, (though not consistently!), quoted by NIST to be less than 50 cm and 8°, respectively

We have used the formula, $\mathbf{d = h\,[\,1 - \cos\theta\,] + w \sin\theta}$, where **h** is the height and **w** is the width of a structure tilted from its normal vertical axis by an angle of θ degrees, to calculate values of the downward displacement, **d**, of the upper sections of WTC 1 & 2 prior to collapse. Thus, for example, we calculate a downward displacement of about 230 cm for WTC 2 at a tilt angle of 2°. This is almost 8 times larger than the downward displacements reported by NIST for WTC 2, (about 45 minutes after the aircraft impacts), in Figure 4-89 (page 256) of Chapter 4, Section 1-6D, of the NIST Report.

Most unfortunately, however, NIST is *not* consistent in its reporting of the tilting of WTC 2 prior to collapse. Thus in Figure 9-14 (page 308) of Chapter 9 we read in reference to WTC 2 just before global collapse:

> "*The entire section of the building above the impact zone…began tilting as a rigid block about 7° - 8° to the east and about 3° - 4° to the south. …. The building section above impact continued to rotate to the east as it began to fall downward, and rotated to at least 20 to 25 degrees.*"

However, on page 169 of the NIST Report, in a Section called *Observations and Timeline of Structural Events,* we read in reference to WTC 2, (See item 11 of Table 6-2):

> *" The building section above the impact area tilted to the east and south. …. Rotation of approximately 4 to 5 degrees to the south and 20 to 25 degrees to the east occurred before the building section begins to fall vertically*."

Thus we see NIST claiming, on the one hand, that WTC 2 "*rotated 20 to 25 degrees* ***as it began to fall***", while on the other hand claiming elsewhere that WTC 2 "*rotated 20 to 25 degrees* ***before it began to fall.***"

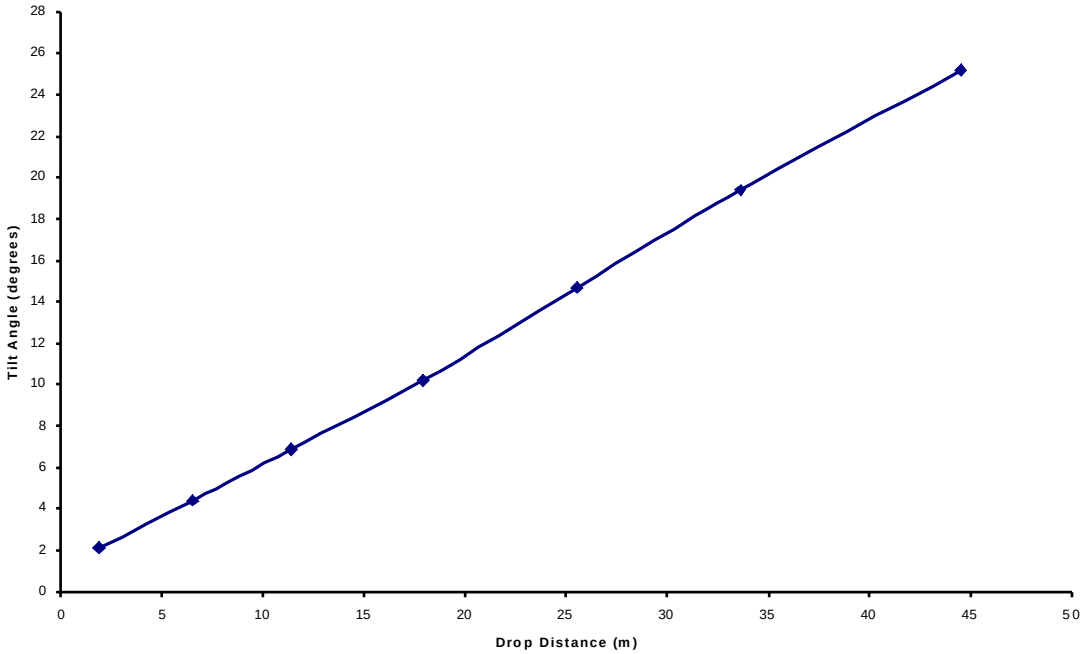
The suggestion that WTC 2 rotated by up to 25 degrees *before* it began to fall is very significant since it would indicate that the top of *WTC 2 fell over rather than fell down!* This is an entirely different mode of failure to the oft-quoted progressive collapse or "pancake theory"; we therefore need to take a closer look at the first stages of the WTC 2 collapse. Even a cursory viewing of WTC 2 collapse videos confirms that the upper section of the building tilted at the start of the collapse. However, trying to estimate *when* and *by how much* such tilting occurred is difficult because of two factors:

(i) Perspective – the viewing angle of a particular photograph or video greatly complicates the interpretation of how WTC 2 fell and must be allowed for in the measurement of tilt angles. For example, foreshortening of the tilting to the east of the upper section of WTC 2 is quite significant in the well-known NBC video shot from a location to the northeast of WTC 2. In fact the *apparent* tilt angle in this video is only about 40 % of the *true* tilt angle.

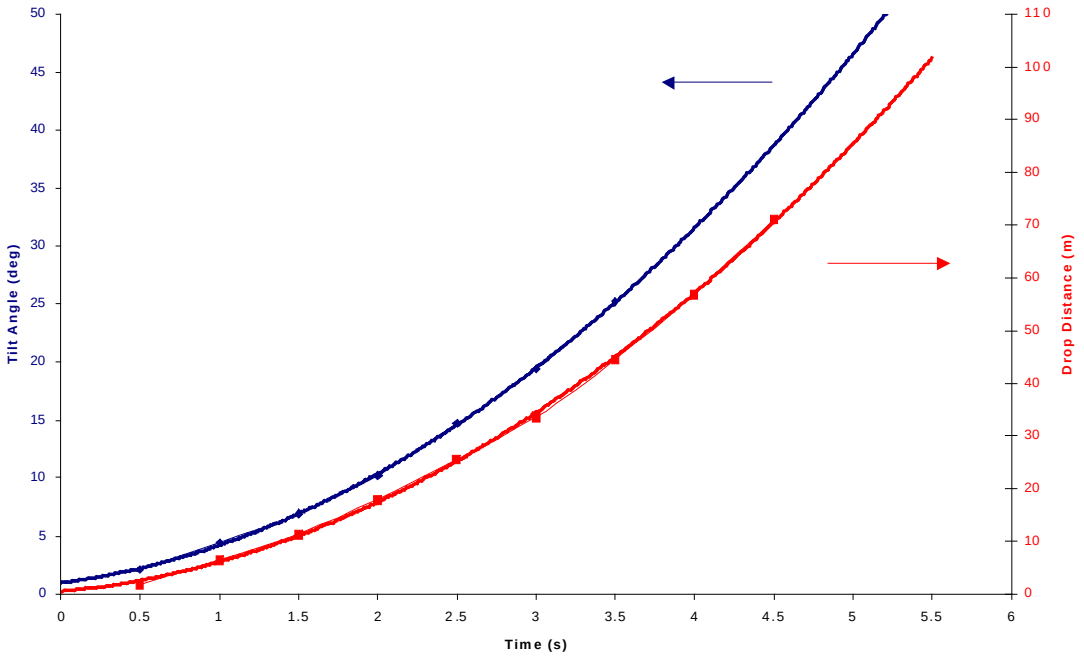
(ii) The timing of the start of collapse. The first motion of the upper section of WTC 2 is stated by NIST to occur at 9:58:59, a moment when smoke and debris clouds were expelled from near the 80th floor on the E, N, and W faces of the building. However, the NBC video noted above shows that there was a delay of at least a second after the appearance of a band of white smoke near the 80th floor and noticeable tilting of the east face of the Tower. This is a significant source of timing error considering that WTC 2 was tilting at a rate of about 10°/sec only a few seconds into the collapse.

Because of these uncertainties we have not attempted to measure tilt angles less than about 0.5° in our analysis of the WTC 2 collapse videos. We have instead measured tilt angles and drop distances that are several seconds into the collapse and subsequently extrapolated to zero drop distance to determine the tilt angle, $\boldsymbol{\theta_o}$, at the collapse initiation time, $\mathbf{t_o}$. Once a time scale has been established in this way, the variation of tilt angle $\boldsymbol{\theta}$ and drop distance **d** with time **t** may be determined with good precision. Results of these determinations for WTC 2 are shown in the Figures reproduced below.

WTC 2: Tilt Angle vs. Upper Section Drop Distance



WTC 2 : Tilt Angle and Drop Distance vs. TIme



The results presented in the above Figures show that the tilt of WTC 2 *before collapse* was only about 1°, in apparent contradiction to the NIST Report. However, NIST's assertion that WTC 2 was tilted by 8 or more degrees *before collapse initiation* may be reconciled with our analysis, if the "dropping" of the upper section of the Tower is considered to be *a rotation about a fixed point, rather than a vertical descent*. This view of the early stages of the WTC 2 collapse brings us back to the idea that, at least initially, the upper section of WTC 2 fell over rather than fell down. But is this view of the WTC 2 collapse a valid interpretation of the actual event?

An answer to this question may be found by applying the formula,

$$\mathbf{d = h\,[\,1 - \cos\theta\,] + w\sin\theta},$$

to the *observed* tilt angle data for WTC 2 presented in graphical form in the Figures above. The θ values in question are also presented in Table 2, below, together with the *observed* drop distances and the *calculated* "rotational drop" distances derived from our formula. It is seen that the observed drop distances are consistently *larger* than the calculated rotational drop distances. We attribute the difference in these distances to a "true" vertical drop component of the upper section of WTC 2.

Table 2: WTC 2 Tilt Angles and Observed and Calculated Drop Distances

Time (s)	Tilt Angle (degrees)	Observed drop distance (m)	Calc. rotational drop distance (m)	True vertical drop distance (m)
0	0	0	0	0
0.5	1.0	1.9	1.1	0.8
1.0	2.1	4.0	2.4	1.6
1.5	4.4	11.0	5.2	5.8
2.0	6.9	17.9	8.5	9.4
2.5	10.2	25.5	13.1	12.4
3.0	14.7	33.6	19.9	13.7
3.5	19.4	44.5	27.6	16.9
4.0	25.2	56.9	37.8	19.1

The data in Table 2 clearly demonstrate that the collapse of WTC 2 involved a combined (simultaneous) rotational and vertical dropping motion of the upper section of the building. Furthermore, these motions started at about the same time and were approximately equal in magnitude over the first 2 seconds of collapse; thereafter, the descent of the upper section was increasingly dominated by rotational motion.

Energy Analysis

In our report entitled *Energy Transfer in the WTC Collapse Events of September 11th 2001* we have used momentum transfer calculations to determine the collapse time, t_c, for each WTC Tower and have also introduced the quantity E_1, the energy required to collapse *one* floor, as a variable parameter. E_1 represents the work of collapse. This work is done against an effective force of resistance, F_R, provided by the columns and other support structures in the Twin Towers.

We have previously modeled the resistive force F_R as a series of short-duration impulses acting at the moment of impact of a descending block of floors with the floors below. However, it is also possible to consider F_R as a *continuously acting force* similar to the drag force associated with wind resistance. In this case, because E_1 represents the work performed in collapsing *one* floor, the necessary work is accomplished over a distance of 3.7 meters. Hence, we may write:

$$E_1 = F_R \times 3.7 \text{ Joules}$$

or,

$$F_R = E_1 / 3.7 \text{ Newtons}$$

It follows that the net downward force, F_D, acting on a descending upper section of a WTC Tower is given by,

$$F_D = Mg - F_R = Mg - E_1 / 3.7 \text{ Newtons},$$

where M is the mass of the upper section and g is the acceleration due to gravity.

Using Newton's First Law of motion we may now define the effective downward acceleration, a_{eff}, of the upper section of a WTC Tower as follows:

$$F_D = Ma_{eff} = Mg - E_1 / 3.7 \text{ Newtons}$$

Hence,

$$\mathbf{a_{eff} = g - E_1 / [3.7M] \quad m/s^2}$$

If a_{eff} is determined by direct observation of the collapse of a Twin Tower, E_1 may also be estimated using the above equation. Furthermore, since we have shown that E_1 is equivalent to NIST's potential energy loss, $\Delta E = Mg\Delta d$, where Δd is the downward displacement of the upper section of floors *prior to collapse*, we may write:

$$\mathbf{a_{eff} = g \{ 1 - \Delta d/3.7 \} \quad m/s^2}$$

Qualitatively these equations for a_{eff} show that if E_1 is *small*, the columns in a Tower offer little resistance to excessive strain and global collapse occurs at a rate *close to free fall* or an acceleration of 9.81 m/s^2. A *small* E_1 also implies that the strain limit of a Tower is reached for *small* downward displacements or tilt angles (See below).

At the other extreme, a *large* E_1 means that a_{eff} is much *less* than g and global collapse occurs at a rate well *below* free fall. Similarly, a *large* value for E_1 means a Tower is able to tolerate *large* downward displacements without collapsing. Clearly, if a downward displacement reaches the floor height of 3.7 meters *without initiating a failure of the floor*,

$$a_{eff} = g \{ 1 - 3.7 / 3.7 \} = 0,$$

and global collapse does not occur.

The observational data in Table 2 show how these ideas may be put on a quantitative basis for the collapse of WTC 2. We have taken the observed drop times and drop distances and calculated the effective acceleration, a_{eff}, using the well-known relation: distance = ½ a_{eff} t^2. The resulting values are reproduced in Table 3.

Table 3: Effective Acceleration of the Upper Section of WTC 2 After Collapse Initiation

Time (s)	Observed drop distance (m)	Effective acceleration (m/s^2)
0	0	-
0.5	1.9	6.1
1.0	4.0	8.0
1.5	11.0	9.8
2.0	17.9	9.0
2.5	25.5	8.2
3.0	33.6	7.5
3.5	44.5	7.3
4.0	56.9	7.1

The data in Table 3 show that the effective acceleration, a_{eff}, although not strictly constant, is tending to a steady value ~ 7 m/s^2. If we substitute this value into our equations relating a_{eff} to E_1 and Δd, we arrive at:

E_1(WTC 2) = 1.4×10^9 Joules and Δd(WTC 2) = 1.06 meters

Additionally, using distance = 416 meters = ½ a_{eff} t_c^2, we estimate the **WTC 2 collapse time, t_c, to be 10.9 seconds** - a value well in-line with our previous estimates for t_c.

Similar data may be collected for the collapse of WTC 1. Typically a_{eff} is observed to be ~ 5 m/s^2 in which case **t_c for WTC 1 ≈ 12.9 seconds**. It follows that:

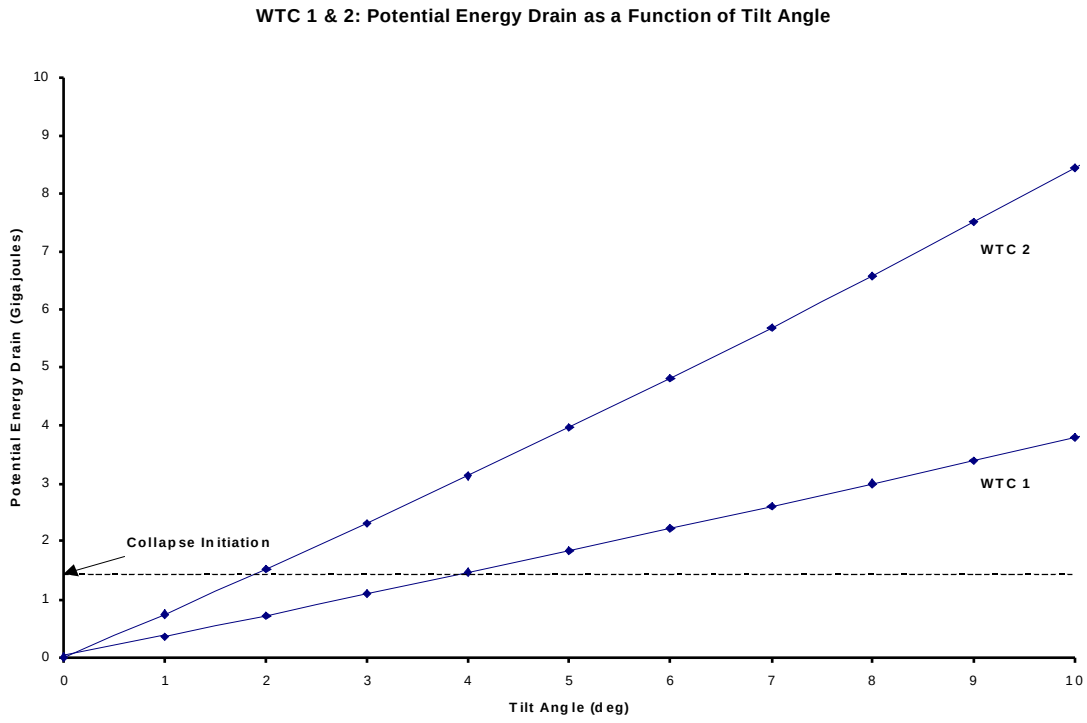
E_1(WTC 1) = 1.2×10^9 Joules and Δd(WTC 1) = 1.81 meters

Thus we see that our estimated E_1 values for WTC 1 and 2 are consistent and fall in the range $1.2 - 1.4 \times 10^9$ Joules. However, we also find that **WTC 1 required almost 2 meters of downward displacement in the upper section of the building to initiate collapse**. **This is about two times the downward displacement required for the collapse of WTC 2, and six times NIST's estimate of Δd(WTC 1) of about 30 cm.**

The detailed calculations of the deformation of the upper sections of WTC 1 & 2 carried out by NIST show that the downward displacements within the Twin Towers were not strictly vertical but involved tilts in the direction of the impact damage. Such tilts are easily included in our energy calculations using the fact that the lowering of the center of gravity, Δd_{cg}, of an upper section of each Tower (as a function of tilt angle θ) is given by:

$$\Delta d_{cg} = \tfrac{1}{2} \{ h [1 - \cos \theta] + w \sin\theta \}$$

where h and w are the height and width of the upper section of the Tower, respectively. Application of this formula to the tilting of the upper sections of WTC 1 & 2 shows that a 2° tilt was required to bring WTC 2 to collapse initiation while a 4° tilt was required for WTC 1. This is shown graphically in the Figure below.



We have previously discussed the tilting of WTC 2 prior to collapse and noted that a 2° tilt of the upper section is the *largest* possible pre-collapse angle that is consistent with observations of WTC 2. For WTC 1, in spite of the presence of a TV antenna on the roof as a convenient angle marker, clear views of the top of the building are frequently hampered by heavy smoke. Nonetheless, we can safely say that the tilt of WTC 1 *at collapse initiation* was less than 3°. We acknowledge that photos of WTC 1 shown on page 166 of Chapter 6 of the NIST Final Report appear to show tilts of the TV antenna on the roof of WTC 1 as large as 8°. However, these photos were taken *at least 2 seconds after collapse initiation*. Thus, while there is no question that both WTC 1 and WTC 2 tilted quite markedly as they fell, there is no indication of any tilting of the upper sections of either building that was greater than 3° *prior to collapse initiation*. Tilts greater than this would have been very obvious in photos of the Towers taken from appropriate locations – after all, the tilt of the famous Leaning Tower of Pisa is only about 5°, and yet *we easily recognize such a tilt to be quite substantial*.

Conclusions

The NIST mechanism for the collapse of WTC 1 & 2 assumes that the potential energy of Tower sections above the impact zone was slowly, yet irrevocably, converted to strain energy in core and exterior wall columns located below the impact zone. NIST propose that this potential energy drain, caused by the tilting and slumping of floors in the impact zone, eventually exceeded the yield limit of a sufficient number of columns to precipitate global collapse.

To put this description of the collapse of WTC 1 & 2 on a quantitative basis NIST use a complex finite element computer model to calculate the magnitude of downward displacements of upper sections of the Towers after aircraft impact and estimate *maximum displacements* of only about 30 cm. In contrast, using a simple energy analysis of the collapse, we have shown that NIST's small downward displacements lead to inferred collapse energies that are too low to be acceptable – we know the Twin Towers would not collapse that easily. Further, we show from the geometry of a "Leaning Tower" (with the dimensions of a WTC Tower) that a downward displacement of 30 cm requires a tilt angle of less than ½ degree. Remarkably, however, NIST suggest that tilt angles before collapse initiation were more than 4° for WTC 1 & 2. Thus it is evident that the NIST *Final Report* first *underestimates* the downward displacements within the Twin Towers, only to later *overestimate* the initial tilt angles to justify the collapse.

Clearly, if NIST's computer model is essentially correct, the Twin Towers collapsed (or fell over!) at ridiculously small downward displacements and tilt angles, and were inherently unstable as soon as they were struck by aircraft. This raises serious questions about the design and construction of the Twin Towers. However, a more reasonable assessment would be that NIST's computer model is *highly inaccurate*, and therefore of no value in explaining the demise of the Twin Towers.

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