Discussion of "What Did and Did Not Cause Collapse of World Trade Center Twin Towers in New York?" by Zdeněk P. Bažant, Jia-Liang Le, Frank R. Greening, and David B. Benson

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I have read subject article by Bazant et al. with great interest and would like to make the following observations:

There is no need to describe the destruction of WTC1 using differential equations. Simple math plus observations of videos prove the authors' model and paper wrong.

The authors suggests that upper part C (of WTC1) drops on the lower structure of WTC1—part A—that is, *one-way* crushed in 97 steps to the ground. During crush of the first tower, the uppermost story of part A (floor 97) formed a layer of debris—part B—that grows thicker as more stories are crushed by parts B and C. What happens using the authors' model is easily calculated by simple step-by-step calculations. Differential equations are not really required!

Mass and Density of Part C

Near the top, the specific mass of WTC 1 (mass per unit height) $\mu = 1.020.000$ kg/m or 1.020 t/m according, according to the authors. With a story height of 3.6 m, the mass of a storey is thus 3.672 t. Assuming the upper part C is 53 m high (14.7 stories) as suggested by the authors, the total mass of part C above the initiation zone for collapse is 54.060 t. Part C is supposed to drop down and to one-way crush all 97 stories of part A, while part C only suffers "negligible damages." Part A is quite similar structure-wise to part C even if the columns get stronger lower down.

Using a floor area of 4.000 m^2 the volume of part C is 212.000 m^3: thus the uniform (which it is not) density of the upper part C is 0.255 t/m^3 or 255 kg/m^3 according the authors. It is not very much! The reason is that there is plenty of air inside a story structure. The authors assume that the upper part C has some sort of homogeneous structure/density.

Density of Rubble in Part B

The known "typical density" of rubble is $\mu_c = 4.100.000$ kg/m or 4.100 t/m according the authors. The density of this rubble is then exactly 1.025 kg/m^3 (as the floor area is 4.000 m^2), which is the density of salt water (which ships float in).

Thus, when one typical story structure of WTC 1 part A is homogeneously crushed according the authors' model, it becomes 0.896 m high/thick. As it was originally 3.6 m high, it has been compressed 75.1%.

Initiation of Collapse: The First Crush and Formation of Part B

According to the authors, at initiation—part C at 54.060 t (actually the lowest floor 98 of part C)—crushes the uppermost storey of part A (floor 97 of the lower structure of WTC1) and compresses it into a 0.896-m-thick layer of debris/rubble that becomes part B. Air/smoke is ejected sideways. The authors suggest that the local failures are generally due to the buckling of columns between floors 96 and 98, requiring little energy. Energy to *compress* the rubble is not considered by the authors.

This layer, part B, is then resting on the second uppermost floor of part A, which is floor 96. This compression takes place at increasing velocity of part C. Only air is ejected out sideways. The mass of the rubble, 3.670 t, is uniformly distributed on the floor below (918 kg/m^2), and the floor should be able to carry that uniform load according general building standards.

What about the part C and its mass of 54.060 t? Is it acting on the debris layer part B? Not really. Part C is intact according to the authors, but only its bottom floor is now in contact with part B. The columns of part C are now *not* in contact with the columns of part A below due to the layer of rubble, but it must be assumed that part C columns contact the columns of part A below as suggested by the authors, so that crush-down destruction can continue.

The roofline of part C has now dropped 2.704 m after first crush (i.e., story height 3.6 m minus part B height 0.896 m).

The Second Crush: Part B Doubles in Thickness

Then the part C plus part B (the layer of rubble/debris) crush the second-uppermost floor (no. 96) of part A and compresses it into another 0.896-m-thick layer of debris that is added to part B. Part B is thus 1.792 m high or thick after two stories of part A have been crushed. The part C columns now crush the columns of part A again (how?) so that the destruction can continue.

The roofline has then dropped 5.408 m after two crushes! The velocity is increasing. More air/smoke is ejected sideways but only from the storey being crushed.

And so on!

Both the first and second crush is strange in many ways. You would expect the columns in part C between floors 97 and 99 to fail first at impact. The part C columns are weaker than the part A columns below.

The Displacement of the Roofline of Part C during Destruction

According to paper "The Missing Jolt: A Simple Refutation of the NIST-Bazant Collapse Hypothesis" by Graeme MacQueen and Tony Szamboti in 2009 (http://journalof911studies.com/volume/

2008/TheMissingJolt4.pdf) and careful observations of videos of the alleged crush-down we now know that the *roofline* of part C dropped (displaced downward) 35 m in 3.17 s at increasing velocity. This "drop" of part C is also verified by the authors. However, it is not part C moving down that we see: It is part C becoming shorter, while part A remains intact.

Every time a storey is crushed, part C drops 2.704 m and an 0.896 m layer of debris is formed according to the authors, and the part C columns also destroy the columns below (how is not clear as there is a thick layer of rubble), with part B in between!

Thus, when the roofline has dropped 35 m, 12.94 stories, a total height of 46.6 m of part A have been crushed and have been replaced by an 11.56-m thick-layer of debris (part B). A total of 46.6 m of columns of part A have been crushed at perimeter and core, the latter being mixed in the debris. I assume the wall columns are dropping down to the ground outside the building.

MacQueen and Szamboti believe that only 9 (or 9.72) stories of part A have been crushed after 3.17 s, but according the authors it should be 12.94 stories. MacQueen and Szamboti forget that there should be an 11.56-m-thick layer of debris on part A and below the upper part C, when its roofline has dropped 35 m.

Verification of Parts A and B Using Video Recordings of the Destruction

Regardless: Does anybody see an 11.56-m-thick layer of debris (part B) on any video of WTC1 destruction after a 35 m drop of the upper part of WTC1 (part C according to the authors)? Or that 46.6 m of wall columns have disappeared?

And does anybody believe that an upper part C with density 255 kg/m^3 can produce an 11.56-m-thick layer of rubble/debris in 3.17 s? The authors suggest so, but there is no evidence for it, as the authors ignore the energy required to compress the rubble. Simple calculations show that this energy doesn't exist.

This layer of debris is then moving at a velocity of >20 m/s and increasing. The acceleration of parts C and B become rather uniform 0.65–0.7 g (i.e., very little force is applied on part A). Only air/smoke should be ejected from the next story below being crushed, where more debris is formed.

Situation When Part C RoofLine Has Dropped 100 and 200 m

When part C has dropped 100 m and 37 stories (floors 97-60) have been crushed, the layer of debris (part B) should be 33 m thick on top of which a 53-m-high part C should be visible (forgetting the mast). There should be 133 m of walls missing! You do not need differential equations to calculate this. Simple math suffices!

An when part C has dropped 200 m and 74 (floors 97-23) stories of WTC1 have been crushed, the layer of debris should be an impressive 66 m thick with part C still riding on top of it.

Imagine a layer of debris with density 1,025 t/m^3 and 66 m high. With over 4,000 m^2 floor area it is almost a big cube of 264,000 tons of rubble! On top of which part C, at 54,060 t ad 53 m high, floats. Add the rubble (part B), and we have a moving mass that is 119 m high when the part C roofline has dropped 200 m.

Below this 119 m high pile, a story of part D(floor 23) is just being crushed. How the columns of part C, which is 66 m above floor 23, can crush the columns there is not clear; 266 m of walls should also be gone. There are another 23 stories still to crush! About 83 m of WTC1 remains to be crushed. Can it be seen on any video? Note also that upper part C is still accelerating at 0.7 g at this time. The speed is of the order of 45 m/s!

When all 97 floors of WTC 1 (part A) have been crushed, there should be an 83-m-thick layer of debris on the ground plus 53 m of the upper part C on top of it. This is also confirmed by the authors in their Fig. 3(b). Just before the end of crush-down the 53-m-high part C rests on a 92-m-thick layer of debris (density 1.025 t/m^3); the crush down has also penetrated the basement 22 m below ground! The roof line of part C should then be 133 m above the ground.

An instant later upper part C is destroyed in a crush-up, according to the authors, and should form another 13-m-thick layer of rubble (according to another differential equation). The total thickness of rubble should be 92+13=105 m minus 22 m of rubble in the basement=83 m of rubble above ground; but only 20 m is suggested by the authors.

Evidently some rubble is spread outside the 4,000 m^2 footprint, but it seems the density of the rubble must have increased three times, to 3.075 ton/m3! But it is not possible; it is too dense. So where did all the rubble go?

Actually no rubble could be produced at all by dropping upper part C, as the destruction should have been stopped up top due to all local failures developing, when part C contacts part A and friction between all partly damaged parts develops at floor 98. Only by ignoring local failures and friction at first contact between parts C and A is the authors' model initiated. If any further columns would fail, they would have been in part C.

But what the authors' theory and model postulate cannot be seen on any videos of the WTC1 destruction. Simple observations of any video of the WTC1 destruction prove the authors' model wrong.

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The discusser's interest is appreciated. However, he presents no meaningful mechanics argument against the gravity driven progressive collapse model of our paper. His claim that "the authors' theory is wrong" is groundless. Briefly, the reasons are as follows:

Equations of Motion

The discusser claims that no differential equations are required to model the collapse. This is incorrect. The intuitive guesses emanating from his disconnected quantitative estimates prove nothing. Although the discusser uses some mechanics terms such as velocity and acceleration, nothing can be deduced without actually formulating and solving the equations of motion. If the discusser rejects the differential equation form of the equations of motion based on a smeared continuum approximation, he could be credible only if he formulated and solved discrete equations of motion.

Energy Dissipation Sources

The discusser claims that the progressive collapse model we developed in the paper does not consider the energy required to compress the rubble. This claim is absurd. He apparently overlooked that this energy is included in parameter γ of Eq. (11). On p. 898 of the discussed paper it is stated that, aside from the energy of comminution, parameter γ includes "the energy of plastic fracturing deformations of floor trusses with their connections and of horizontal steel beams connecting the perimeter columns, the energy dissipated by inelastic deformation and friction of colliding fragments, the energy of crushing the equipment, drywalls, perimeter walls, furniture, piping, etc."

However, based on simple estimates of the surface areas of all the fractures, fracture energies on these surfaces, plastic strain magnitudes, magnitudes of frictional forces in collisions, and frictional slip distances, it transpires that the combined energy dissipated by the aforementioned processes is much smaller than the energies required for the comminution of concrete into particles, for the ejection of air, dust, and fragments at high speed (representing the work of F_a and F_e). The reason for the dominance of the energy of comminution of concrete is the extremely small size of the particles, ranging from 10 to 100 μm in size, which causes the combined surface energy of these particle to be enormous. All these energies, in turn, are small compared to the energy of plastic buckling of the massive stocky columns (work of F_b), and that energy is again smaller than the energy required to accelerate downward the accreted stationary mass at the crushing front [F_m in Eq. (5)].

Therefore, it is not important to know parameter γ accurately. It was mentioned in the paper that, within the range γ between 0.6 and 1, the calculation results for the motion history, the time to hit the ground, and the amount and size distribution of particles are virtually indistinguishable. So it makes no sense to argue about the precise energy dissipation by the aforementioned secondary processes.

The overall energy balance is ensured by deriving the differential equations of motion from an energy potential [see Eqs. (25)–(30) of Bažant and Verdure 2007]. The necessity of gravity-driven progressive collapse is demonstrated by the fact that the kinetic energy of impact on each floor far exceeds the energy absorption capability of the underlying columns [Eq. (3) in Bažant and Zhou 2002].

Crushing of Columns

The discusser further claims that, for the continuation of the crush-down phase, the columns in the part C (upper part) must be assumed to be in contact with the columns of part A (lower part). This claim is erroneous. During the crush-down collapse, part C and part B (compacted layer) are moving together as a whole while part A is being crushed by the compacted layer B [schematically, see Fig. 2(b) of the paper]. The energy condition for the crush-down phase to continue is given by Eq. (6) of Bažant and Verdure (2007) (and the gravity driven crush-down is actually guaranteed to occur by Eq. (3) in Bažant and Zhou 2002).

Video and Direction of Crushing

Observation of the upper margin of the cloud of dust and smoke in the videos somehow makes the discusser conclude that the tower top motion is caused by "part C becoming shorter while part A remains intact." This is a delusion. Part A remaining intact would violate the principles of conservation of momentum and of energy. The writers' analysis of the initial two-way collapse shows that the columns of part C get plastically squashed by only 1% of their original length and afterward the collapse proceeds in a one-way crush-down mode (Bažant and Le 2008).

The compacted layer cannot be expected to be seen in the video record. Similar to construction demolitions, it is not, and cannot be, located just under the upper margin of the cloud because the rapidly ejected air and dust spreads both downward and upward [Fig. 3(a) in the paper].

Rubble Pile

Based on the profile of the rubble pile shown in Fig. 3(b) of the paper, the discusser estimates the rubble density to have an unrealistic value (3.075 t/m^3). Since this figure is only schematic, his point is meaningless. Besides, he ignores the fact that much of the rubble (characterized by mass shedding coefficient $\kappa_{out} \approx 0.2$ in the paper) has been ejected during the crush-down and that the tall and narrow pile as sketched exists only for a split second just before the moment at which layer B hits the ground. At that moment, the pile immediately begins to spread rapidly outside the tower footprint. If one assumes the rubble pile density to remain constant during spreading, a simple calculation shows the rubble to spread about 60 m outside the tower footprint. This gives for the rubble pile a slope of about 20°, which agrees well with the typical slope of rubble piles seen in the demolitions of buildings.

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