Discussion of "Why the Observed Motion History of World Trade Center Towers Is Smooth" by Jia-Liang Le and Zdeněk P. Bažant

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The authors address a general argument concerning velocity slowing down at each floor as a result of collisions, in which they assume that their model of gravitational collapse from weakening by fires initiated by the plane crashes is correct. They start with an equation of the velocity drop for the top mass only falling one story or less (3.7 m), then claim for the North Tower that the mass of the falling top segment is about 90 times as large as the mass of the first floor that it hits, slowing that velocity by 1.1%, and then they go on to determine its result as it extends and breaks through that floor.

The following four major issues regarding the claims made by the authors are addressed in this discussion: (1) their assertion about the implications of their collapse model for the South Tower; (2) the very inadequate amount of energy expended in their gravitational collapse model, including the claimed ease of breaking through and demolishing each floor that they assert in explaining the smooth collapse, in contrast to independent calculations of the total energy expended in the observed collapses; (3) the underlying one-dimensional (1D) assumption made in the equations used to model the collapse in their paper and in the previous papers they reference (the shortcomings of this 1D model seriously challenge its validity and, thus, also challenge the "crush-down, crush-up" model of gravitational collapse for the calculations they present); and (4) their broad claim that all objections have been shown invalid is challenged.

Looking first at the velocity of collapse used for their model, their discussion ignores the observed collapse of the South Tower's top segment that the model does not explain—it is obviously not being crushed down, even though it is collapsing from the top down. When the photographic evidence of the collapse sequence of the South Tower is viewed, the viewers see fall rates for the top segment of the tower that vary with time, which in the initial second or more of its collapse are much faster than gravity could produce. This top segment collapses by itself (it is not being crushed down or crushed up), and gravity certainly cannot have caused it, because it initially collapses at an acceleration rate more than four times that of gravity.

The authors first mention the South Tower in the original paper by quoting a calculation from their gravitational model, similar to what they have done for the North Tower, for the maximum displacement (0.84 mm) of the first floor hit in their model (which is below the fire zone for the South Tower) caused by deceleration from the assumed moment of impact. This location is, indeed, where the collapse action started because it began with white squibs shooting horizontally out the sides just below where the fires were (their 1D model neglects this horizontal motion), and very shortly afterward the top segment (top 33 floors) of the tower started leaning. Then, the top 33-floor segment above where the white squibs came out suddenly began spurting gray dust out of its lower sides before the bottom segment started coming down. The authors discuss the collapse at the 77th floor (where the squibs came from) as the start of the South Tower coming down (the crush-down phase of their model) and ignore the very rapid collapse and disintegration of the top segment just as the 77th floor and floors just below it were coming apart.

The bottom 77-floor segment had, at most, just started disintegrating at its highest floors when that top segment began rapidly collapsing and disintegrating, a process incompatible with their crush-down, crush-up model. A measurement of how fast the top of the top segment started coming down yields about 24 m (± 1 m) in the initial 1.0 s. This distance is substantially greater than could be covered in that short time from gravity alone by over a factor of 4. That rapid collapse cannot be caused by gravity. Rather, it appears to be an internal force, much like that producing the white squibs coming out of the lower segment at the 77th floor and the gray dust coming out of the lower sides of the tower's upper segment. The initial very fast rate of the top segment collapse (when the bottom segment had, at best, barely started falling) shows that gravity was not causing it. The energetic ejections of gray dust from the lower part of that top segment indicate that it was likely being pulled down by a force created by large pressure gradients. An explosion inside that top segment, which produced the high pressure that was quickly relieved at the lower levels by the gray dust coming out lower down, could have produced the rapid collapse that was observed.

The observations show that the bottom segment was falling from gravity at a slightly slower rate than that produced by gravitational acceleration. The authors' claim that falling matter hitting the floors caused an imperceptibly small slowdown would imply that the amount of the energy expended in the fall to overcome friction can only be a small fraction of the gravitational potential (MgH, where M is that total mass and H is the mass-weighted average height) of the towers. That expenditure in their model is, at most, about 0.206 MgH from the minimum value of the alpha parameter the authors claim in their Eq. (1), assuming their maximum value of energy is the same for each floor that was broken through. However, independent calculations of the energy expended in the collapses of the towers have produced estimates of that expenditure to be at least 25 MgH or more (Hoffman 2003). This implies that the crush-up, crush-down model cannot begin to account for the energy expended in the World Trade Center (WTC) collapses—indeed, from the maximum energy expenditure claimed in the original paper, over a factor of 100. Hoffman (2003) identified energy being expended for crushing the concrete, heating the concrete and the suspended gases, and vaporization of the water. Any rough validity to these energy expenditure calculations would imply that these collapses cannot be caused by fire-induced gravitational collapse as the authors presume in their original paper.

Another question is raised by the authors' claim of the computed ease of breaking through the first floor. Were the towers so poorly built as to cause such little resistance after part of the upper floors were burnt by fires from the planes—despite being constructed with specifications for tolerating a plane crash? Not according to the tests carried out by NIST metallurgy experts (at the behest of the NIST Committee) (Banovic et al. 2007), who concluded that the whole tower met all the specifications given for the soundness of the tower. Those specifications maintained structural integrity against a direct plane crash, so the towers were well designed for a plane crash. It is not believable that a plane crash could possibly have left them

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so vulnerable to collapse, much less collapsing as quickly as they did with the fires it started.

The third issue is the underlying assumption in the computer model that the authors use for their numerical calculation in the second section in their paper, with the computer model discussed in more depth in Bažant and Verdure (2007) and in Bažant et al. (2008). The crucial limits of the 1D assumption used in these equations seriously challenge their validity for the complex three-dimensional structure of the towers and, thus, of the crush-down, crush-up model of gravitational collapse that they represent. Bažant et al. (2008) introduced equations they say are generalized in Appendix 2 of their paper, which includes a more-detailed model that considers crushing in both directions. They subsequently solved those equations in their reply to criticism from Gourley (2008) for not including crushing up at the same time as they did crushing down (Bažant and Le 2008). However, their generalized equations are still 1D.

The authors' equations encompass an implicit 1D structure of the towers, and they make all their calculations in the original paper using one dimension in their crush-down, crush-up model. The motivation for 1D equations appears to be expressed in Bažant (2000) in which, after pointing out in Section 5 that "long thin-walled beams" can be approximately treated such that their differential equation for the equation of motion is 1D, Bažant (2000) says "for open cross-sections the most important deformation mode is the warping of the cross-section, with the bimoment being the associated force variable." Bažant (2000) apparently assumes that warping the cross section in the gravitational force direction is the only important process for the towers. Is that vertical dimension, the direction of gravitational force, the only important dimension in those collapses? Le and Bažant 2010 defended these equations as being necessary against the comment by Bjorkman 2010, despite his efforts to demonstrate that just basic principles of physics show the gravitational collapse of their model is not possible. However, in fact, this 1D equation cannot model the towers' collapses correctly because the horizontal dimension is very important in the physics of those collapses. This includes the squibs repeatedly shooting out in this horizontal dimension, the South Tower's top segment making a sudden shift in the horizontal direction in its collapse, and very large pieces hurled out from both towers, having considerable momentum and kinetic energy in this horizontal dimension. There were large streams shooting out in the horizontal dimension with large debris coming out from the towers—not only with a downward component but also an upward component in the case of the North Tower. These effects are all neglected in a 1D model, yet they are very important processes in the towers' collapses.

The towers were definitely not 417-m telephone poles (as 1D models would imply). Such tall telephone-like poles would be far more unstable to a gravitational collapse than the towers; however, even they also would not collapse by the crush-down, crush-up model. A pole-type structure would collapse by breaking into pieces on the way down, a process requiring at least two dimensions to describe it.

The fact is that the towers had 287 or so columns spread over the horizontal dimension, and these columns were designed to take a load of up to 2,000% of their weight, such as the load created by other buckled columns, all producing a shift of the position of weight bearing in that horizontal dimension. These critical effects are all improperly treated in the 1D model, which ignores the horizontal extensions of the towers and completely neglects the interlocking internal structure that would be a major resistance to such instabilities—indeed, also a major resistance to anything close to near free-fall conditions that the authors are asserting in their model. The towers were well constructed over 4,000 m^2 horizontally with interlocking structures to provide for very high stability, and all of that is ignored in the simple 1D model that is the primary focus in the original paper and the several papers referenced (see also Grabbe 2010). The crush-down/crush-up equations are totally inadequate for describing the observed tower collapses, giving very misleading solutions.

Finally, the discusser challenges the authors' statement at the beginning of their paper where they say "All the objections of the proponents of the controlled-demolition hypothesis have been shown invalid." In particular, that is not correct in their response to the recent comment by Bjorkman (2010) (Le and Bažant 2010), who challenges the validity of the 1D model based on observations, as well as on an earlier critique by MacQueen and Szamboti (2009). Bjorkman (2010) states that the equations are not needed to see from observations that the authors' model is wrong. The authors disagree with that, responding that the equations are vital. However, questions of the collapse of the towers are at least 2D because of important features observed in the horizontal direction. The authors' 1D gravitational equations for that analysis are not adequate, and they cannot counter the objection by Bjorkman (2010) unless they present a quantative model of the tower that is at least 2D in their equations of motion.

One point in the conclusion by Bjorkman (2010) that is correct needs to be backed up. Bjorkman notes that, in the authors' collapse model, "the destruction should have been stopped up top due to all local failures developing, when part C contacts part A and friction develops between all partly damaged parts at floor 98," pointing out that they neglect the friction in these failures. The accuracy of this statement can be understood from the principles of energy and momentum conservation. The momentum and energy conservation principles are ironclad, and the discusser pointed out their implication for the collapses in Grabbe (2008). The Twin Towers were, as are all tall buildings of course, architecturally built such that the mass decreases with height, and the conservation principle implies that the top segments (14 floors for the North Tower; 33 floors for the South Tower) do not have enough energy and momentum to completely gravitationally crush down the lower floors, which have greater massive bulk; therefore, any initiated collapse would soon be arrested. The authors' calculations in the original and previous papers apparently violate energy and momentum conservation, and Bjorkman (2010) says they are untenable.

Regarding these questions of gravitational collapse and the 2D nature of the collapse that is challenged in the authors' paper, the discusser invites, for comparison, a conference presentation on what was probably the world's worst fire in a skyscraper, and the only one that ever caused partial collapse of a building: that of the Windsor Building in Madrid, Spain, in 2005 (Ikeda and Sekizawa 2005). Unlike the fires in the towers of the WTC, which collapsed after 1:41 (North Tower) and 0:56 (South Tower), the Windsor Building continued for 22 h, and its flames on the top of the building were much more widespread and intense than those atop the North Tower. The very top of the Windsor Building partially collapsed at the top but the rest of the building did not collapse. Indeed, the collapse was arrested after part of the top collapsed, as would be expected because of the inhomogeneous nature of fire destruction. Clearly, looking at the details of that paper, that collapse was 2D in nature, and none of the floors as a whole collapsed. It was the perimeter columns of the top floors that collapsed but not the central top floor columns or any other part of the building. There is no means by which anyone could even begin to describe this fire-induced collapse with 1D equations.

The Windsor Building was steel-reinforced (whereas the WTC buildings were full steel buildings). However, even after burning for 22 h the fires did not appear to take out that steel-reinforcement—only the nonmetallic parts of the floors. It is not reasonable to claim

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that fires could seriously degrade the metallic structure throughout the towers in the under-2-h time interval for the North Tower and under-1-h time for the South Tower. However, hundreds of pieces were flying out in all different directions in the WTC collapses, a highly dynamic condition very different from the Windsor Building with very limited partial collapse.

This example indicates how quite unbelievable it is that the interlocked steel structure and steel floors completely collapsed all the way down only from fires in the WTC Twin Towers. The following conclusions are drawn: (1) the collapses were filled with significant motion in the horizontal direction; (2) the energy/momentum conservation and energy inadequacy problems with the gravitational model contradict the observed collapses; and (3) the fundamental problems with the authors' 1D model indicate it is inadequate to correctly model the collapses. All of these demonstrate that the claims made by the authors on why the collapses were "smooth" are not correct.

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The discusser's interest is appreciated. However, his objections against the analysis of gravity-driven progressive collapse of the Word Trade Center (WTC) towers by have no scientific merit, for the following reasons:

1. The discusser claims that, based on the photographic evidence of the collapse sequence, the downward acceleration of the falling South Tower was much higher than the gravity acceleration. This claim is supported by no references and no measurements, and the conflict with various evidence is ignored. In contrast, Bažant et al. (2008) analyzed in detail the video record of the collapse and showed the collapse to be, for the South Tower (after the lapse of 2 s), 10.5% slower than the free-fall velocity, and for the North Tower (after the lapse of 3 s) 17.4% slower; see Fig. 7 in Bažant et al. (2008).
2. The discusser claims the energy expenditure implied by the minimum value of α in Eq. (1) of the original paper to be incorrect because of being 100 times smaller than the energy expenditure given in the online posting of Hoffman (2003). This claim is groundless for the following two reasons:
   a. Hoffman's calculation is incorrect. For example, without any justification, Hoffman simply considered the energy required for comminution of concrete to be 1.5 kW·h/t. This is about 10 times larger than the value obtained by Bažant et al. (2008), which was calculated by means of the well-established and generally accepted comminution law using the known value of fracture energy of lightweight concrete. Furthermore, Hoffman (2003) considered that, to explain the observed fast ejection of air and dust, the concrete fragments as well as the air had to be heated by 720°C, which would, of course, require a huge amount of energy. However, this is incorrect since the cause of air and dust ejection is not purely, and not even mainly, the thermodynamic expansion. Bažant et al. (2008) considered the distribution of momentum upon impact and calculated the velocity of air as it was ejected from the collapsing stories, and it turned out that the required energy dissipation was far smaller than Hoffman's value.
   b. Parameter α considered in Eq. (1) of the original paper mainly accounts for the energy dissipated by the plastic buckling of heated columns at the initial collapse story. Bažant et al. (2008) showed that, at the beginning of collapse, the energy dissipations due to concrete comminution, air and dust ejection, etc., were negligible compared with the energy dissipation due to column buckling. Subsequently, the total energy dissipation per story was rapidly increasing as the collapse proceeded and, thus, it is obvious that the energy dissipation for the first collapsed story was less than

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the average energy dissipation per story. Therefore, it makes no sense to compare the energy expenditure implied by Eq. (1) of the original paper with Hoffman's incorrect calculation.

3. The discusser questions the ease of breaking through the first floor of the WTC towers. This has been thoroughly analyzed in a series of papers, particularly in Bažant and Verdure (2007), Bažant et al. (2008), and Bažant and Le (2008). To sum up, the gravity moment caused by the eccentricity of the aircraft impact caused the surviving columns at the margin of the zone of the collapsed column to be loaded, right after the initial blast, near their cold capacity. The sustained heating of many columns that had been stripped by the blast of their thermal insulation gradually reduced their yield strength, which inevitably led to viscoplastic (or creep) buckling. Heating to 150°C and yield strength reduction by 10% suffice to explain such delayed buckling. A further aggravating factor is that some columns in the fire zone were seen in photographs to be bowing, laterally unsupported, over the height of several stories.
4. The discusser questions the validity of the one-dimensional (1D) dynamic collapse analysis by claiming that it neglects the streams of debris shooting out horizontally from the towers, as well as the load redistribution within the floor. This claim is incorrect. Although the 1D model does not model these phenomena explicitly, Bažant et al. (2008) took them into account through the corresponding energy dissipation terms in the 1D dynamic crush-down equations. The fact that these energy dissipations were captured realistically is documented by the fact that the 1D collapse equation accurately predicts the collapse duration as well as the velocity of the crush front (Bažant and Verdure 2007). The 1D gravity-driven model by Bažant and Verdure (2007) and Bažant et al. (2008) has been shown to be consistent with all the observations, which include the tower motion history, the size distribution of the pulverized concrete particles, the extent of air and debris ejection, and the total collapse duration.
5. Without attempting any mathematical argument, the discusser claims that the calculations by Bažant et al. (2008) and in the original paper violate the principles of energy and momentum conservation. This is baseless. The equations of motion proposed by Bažant and Verdure (2007) and Bažant et al. (2008) were rigorously derived from these principles. Bažant and Le (2008) and Bažant et al. (2008) discussed in detail how the model captures the energy dissipations by various mechanisms such as column buckling, concrete comminution, and air and debris ejection.
6. Again, with no mathematical analysis, the discusser claims that because the mass of the WTC towers decreases with height, the top segment would not have sufficient energy to crush the massive lower part of the tower. This is incorrect. Based on the energy conservation, Bažant and Zhou (2002a, b) showed that the forces in the columns caused by the vertical impact of the entire upper falling part exceeded the initial load capacity of the lower part by an order of magnitude. Therefore, the collapse was inevitable.
7. The discusser makes a comparison between the collapse of the WTC towers and the Windsor Building. However, such a comparison is meaningless because these two buildings have different structural elements and the cause of collapse is totally different. The Windsor Building has a massive reinforced concrete core whereas the core of the WTC towers was made of steel columns. Under fire, the reinforced concrete core remained intact since concrete has very poor thermoconductivity. In contrast, the steel columns in the core of the WTC towers were weakened by sustained high temperature, aggravated by the stripping of the thermal insulation of the steel during the initial blast. Furthermore, the initial damage of these two buildings is totally different. The steel columns in the Windsor Building were subjected to normal service loads under the fire. For the WTC towers, aircraft impact damaged many columns, and the surviving columns of the WTC towers experienced significant overloads, reaching in some of them up to their cold strength because the eccentricity of the aircraft impact damage engendered a significant gravity bending moment in both towers. At the initiation of collapse, only a part of the story of the Windsor Building collapsed at first, and in that case a three-dimensional analysis of the collapse is necessary. By contrast, the initial collapse front of the WTC towers immediately spread over the entire floor, and the height-to-width ratio of the towers was sufficiently high to allow a 1D analysis. Finally, the collapse of the Windsor Building was arrested at the 17th floor due to the massive transfer structures at that floor.

   Similar to the Windsor Building, the 41st, 42nd, 75th, and 76th floors of the WTC towers, which carried heavy mechanical equipment, were strengthened by structural steel frame slabs. They were designed to distribute the equipment weight laterally, but they could neither arrest the vertical collapse of WTC towers nor reduce the collapse velocity appreciably. They were not designed for that purpose anyway. When the crush font reached these floors, the accumulated kinetic energy was already far higher than the energy required to crush these frames. Therefore, the discusser's intuitive comparison with the partial collapse of the Windsor Building is baseless.

It is surprising to see that references to online postings and an online journal not subjected to mechanics reviewing are cited as evidence. A further problem of discussion is that it is written without the use of the standard simplifying hypotheses of structural mechanics, which make the structural analysis feasible, are justified by vast experience, and represent the essential content of structural mechanics courses and textbooks. The discusser's objections to the gravity-driven collapse analysis presented in the original paper are invalid. His conclusion that "The analysis by Le and Bažant is incorrect" is groundless.

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