International Journal of Engineering and Techniques - Volume 8 Issue 5, September 2022

RESEARCH ARTICLE OPEN ACCESS

Review of Literature Regarding Progressive Collapse of WTC Twin Towers – A Call for Re-evaluation (Updated Version 2)

Adam Taylor, B.Sc.[1]

1 (Bachelor of Science in Management, Franciscan University of Steubenville, 2014
Email: ataylor_email@aol.com)

Note: This is an updated version of **Taylor 2022**. Changes include: Additional studies added (Ross 2006a, 2006b; Greening 2006; Eastman & Cole 2013; Le & Bažant 2017, 2022), corrected typos, superficial cleanup.

Abstract:

Since the tragic events of September 11th, 2001, the official view endorsed by the National Institute of Standards and Technology is that the Twin Towers of the WTC complex suffered a "progressive collapse," wherein the upper sections crushed the lower floors as they pancaked all the way to the ground. This general scenario has become the de facto explanation for the collapse of the Towers, supported by the majority of the engineering community. However, a review of relevant literature on the collapses casts significant doubt on this scenario, showing that a progressive collapse model would have resulted in a longer time to collapse, or perhaps a collapse that would not have progressed at all. As such, re-evaluation of the collapses and development of other, more plausible models is needed.

Keywords **— Pancake collapse, Progressive collapse, WTC, September 11th**

I. INTRODUCTION

The attacks of September 11th, 2001 resulted in the most catastrophic structural failure in the history of engineering – the collapse of the WTC Twin Towers. The official government investigation, carried out by the National Institute of Standards and Technology (NIST), found that the collapses were caused by the combined effects of the airplane impacts, and the ensuing fires started by these impacts. More specifically, the agency found that, in addition to structural damage, the impacts widely dislodged the fireproofing from the floors that were struck, which in turn made the steel supports more vulnerable to the heat from the fires. Subsequently, the fires caused the steel floor trusses to sag downwards, which in turn pulled in on the Towers' perimeter columns, causing them to bow inward and eventually break, initiating the fall of the upper Tower sections (NIST 2005a). Though this scenario has been largely challenged by several independent researchers (e.g., Douglas 2006; McIlvaine *et al*. 2007; Anon & Legge 2009), our interest is on what NIST *did not* address, rather than what they did.

While significant detail is given to explain what initiated the Towers' collapses, the NIST report provides comparatively little in the way of explaining what happened after this initiation, thereby leaving the entirety of the collapse unexplained. This rather significant blind spot is in fact acknowledged by NIST, writing that the report "includes little analysis of the structural behavior of the tower after the conditions for collapse initiation were reached and collapse became inevitable" (NIST 2005a, xxxvii). Rather than provide a quantitative description of the entire collapse, NIST (2005c, 323) instead refers readers to an analysis published shortly after the attacks by Bažant & Zhou (2002), which attempts to explain the entirety of collapse progression. In this and follow-up studies (Bažant & Verdure 2007; Bažant *et al*. 2008), it was determined that the Towers collapsed through a process known as "progressive collapse," whereby the buildings' upper sections, driven by gravity, crushed the lower sections in a top-down fashion. This process has also been routinely dubbed a "pancake collapse," in reference to the floors pancaking one on top of the other as the collapse progresses. While NIST rejects this as what started the collapse (NIST 2011), they do explicitly acknowledge it occurred during the collapse itself (NIST 2005b, 80).

In the past two decades since the attacks, the model of progressive collapse has been endorsed by the majority of those in the engineering community, largely stemming from support of Bažant *et al*.'s various papers outlining the model. Yet during that same period of time, significant flaws have been highlighted in this model, casting doubt on Bažant *et al*.'s original conclusions. While many of these flaws will be shown in discussions of relevant literature, it's worth highlighting some of the most egregious here in order to establish from the outset why critical re-evaluation of the collapses is needed:

- In their original analysis, Bažant & Zhou assumed the fires on the impacted floors were heated to a uniform temperature of 800°C. However, metallurgical analyses carried out later showed no evidence the steel had reached temperatures higher than 600°C, and only three pieces of steel examined showed evidence of being heated above 250°C (NIST 2005a, 90).
- In Bažant & Verdure (2007) and Bažant & Zhou (2002), the mass of the upper section of WTC1 was said to be 54.18×10^6 kg and 58×10^6 kg, respectively. However, NIST calculated that the mass was in fact only 33.18×10^6 kg (NIST 2005d, 176). This is corroborated by independent analysis (Urich 2007).
- Bažant *et al*. assumed the upper section fell through one story in free fall, essentially assuming an entire floor disappeared to initiate collapse progression. This assumes an initial fall rate of approximately 8.5 m/s. However, actual measurements of the upper section show the initial fall to be closer to 2/3 of free fall, or around 6.13 m/s (Szuladziński *et al*. 2013, 118). Since the square of 8.5 and 6.13 works out to approximately 72.25 and 37.57, respectively, Bažant *et al*. nearly doubles the kinetic energy involved in the initial impact.
- In Bažant & Zhou (2002), the stiffness of the columns was estimated as 71 GN/m. However, the actual stiffness has been calculated to be 7.1 GN/m (MacQueen & Szamboti 2009, 22-24), making the estimation off by a factor of ten and resulting in an overestimate of the potential amplifying impulse.

Regardless of these and other errors, the progressive collapse model (hereafter referred to as PCM) set forth by Bažant *et al*. continues to be accepted by the majority of those in the engineering community. What follows is a discussion and review of literature that dissents from this commonly held view, and presents detailed critiques of the PCM. In addition, literature that supports this model is also reviewed, but found to be just as problematic as Bažant *et al*.'s original analysis.

II. LITERATURE REVIEW

In assessing the validity of the PCM as applied to the Twin Towers, two relevant questions are considered: should collapse have progressed after initiation, and if so, how long should such a collapse have taken? As we will see, much of the literature on record makes a compelling case that the collapse should have been arrested early on during the fall, without progressing fully. Such a conclusion alone is enough to warrant dismissing the PCM as a viable explanation for the Towers' total collapse. But suppose the collapse is allowed to progress – how long should it have taken the buildings to fall under this assumption?

Determining the exact time it took the Towers to fall is fairly difficult, since much of the buildings were obscured by heavy clouds of dust and debris during the collapses. Bažant *et al*. (2008, 903) primarily looked at seismic records to determine a plausible collapse time estimate, arriving at mean durations of 12.82 and 10.49 seconds for the North and South Tower, respectively. However, these estimates only consider the fall time of the sections below the plane impact points, without the upper sections included. According to NIST (2005a, 87), the collapses of WTC1 and WTC2 started at the 98th and 82nd floors, respectively, meaning the upper sections were 12 and 28 floors. The Towers were each 110 stories, 1368 (WTC1) and 1362 (WTC2) feet in height. We can therefore say the floors were, on average, ~12 feet each in height, meaning the upper sections were roughly 144 and 336 feet, ~ 10.5 and 24.6% the height of each tower. Thus, if we increase Bažant *et al*.'s results by 10.5 and 24.6%, we arrive at final collapse times of 14.2 and 13 seconds. For the remainder of this review, we will assume the figure of 14 seconds as the time it took the Towers to collapse, but this should be considered upper bound, as the collapses could have been slightly shorter. With these figures in mind, we can now properly begin our review.

Cherepanov 2005 – 2008. In a series of papers published between 2005 and 2008, Cherepanov (2005, 2006a, 2006b, 2008; see also Cherepanov & Esparragoza 2007), outlines an explanation for the collapse of the Towers via "fracture waves," whereby the buildings were reduced to dust and debris due to fracturing, which propagated through the structures at the speed of sound. While this author finds this explanation rather dubious and is unconvinced by it, Cherepanov contrasts the theory against the PCM, and provides very useful critiques. Specifically, Cherepanov argues, with considerable justification, that the PCM would result in fall times longer than what was observed on 9/11.

In Cherepanov (2006b), the collapse times are estimated, assuming the fall is driven purely by gravity. In one model, Cherepanov assumes zero-resistance, i.e., no support from the columns and inelastic collisions between floors. Likewise, the mass is distributed uniformly during collapse. Under these assumptions, Cherepanov calculates the rate of fall will be 1/3 that of gravitational acceleration. We know gravitational free fall is calculated as $s^2 = (d \times 2) / a$, where d is the distance (in feet), a is the acceleration, and s is the time (in seconds). Substituting 10.7 for a (~1/3 of 32.2, the rate of gravity), this gives a fall time of approximately 15.95 seconds. This we can treat as the lower bound time to collapse.

In a second equation, Cherepanov models the Tower more realistically, assuming the mass is distributed linearly, with the support increasing at the buildings' lower levels. Under these assumptions, the rate of fall is found to be 1/5 that of gravity, resulting in a fall time of approximately 20.63 seconds. This we can treat as the upper bound time to collapse. Either way, both of these figures are higher than the observed fall times observed on 9/11, and thus contradict the PCM.

Ross 2006. This paper acts, in part, as a critique of the analysis by Bažant & Zhou (2002). Primarily, however, it serves as a quantitative analysis of the momentum transfer of the upper section of WTC1. Calculating the total energy available from the upper section's fall (2256 MJ), and the energy needed to initiate collapse (2646 MJ), Ross finds a total energy deficit of approximately 390 MJ. Based on these figures, Ross finds that "vertical movement of the falling section would be arrested […] within 0.02 seconds after impact" (Ross 2006a, 37).

In a reply by Greening (2006), several flaws are highlighted, pointing out that Ross's analysis "is incorrect in at least four important ways," summarized as follows:

- Ross incorrectly calculates the kinetic energy of the falling upper section.
- The energy required to pulverize the concrete in the building is overestimated.
- The initial elastic deflection is incorrectly assumed to propagate 24 stories below the impact point.
- An unjustified safety factor of 4 is assumed in the calculations, when in fact it should be 2.

In response, Ross (2006b) demonstrates that even when his calculations are adjusted to take account of these corrections, the minimum energy deficit is found to be 116 MJ, and thus still results in collapse arrest.

Of secondary interest in this reply is the estimation of the minimum time to collapse, if we assume the fall is allowed to progress beyond the first impacted floors. Assuming a "momentum only analysis" and a collapse "progressing from initiation level to the ground level," with the mass per floor emulating that of the Tower, the minimum time to collapse is found to be 13.5 seconds. When the calculation is repeated, but energy is assumed lost through concrete pulverization, the fall is more realistically found to be 17.5 seconds (Ross 2006b, 16).

Important to note are two relevant caveats to these estimates: (1) the calculations only apply to the section below the plane impact point, without the upper section included, and (2) Ross assumes the descending upper section to be 16 stories, rather than 12. A 16-story upper section, roughly 198 feet in height, represents approximately 14.4% the total height of the Tower. Thus, increasing Ross's estimates by this figure results in a minimum time to collapse of 15.44 seconds, and a more realistic time to collapse of 20.02 seconds.

These figures, it should be noted, are close to Cherepanov's findings, and are still conservative estimates, as they take no account of the energy needed to distort the steel or eject debris outside the Tower's perimeter. As these results show, the time to collapse, assuming parameters favorable to the shortest possible collapse time, is still found to be slightly higher than what was observed on 9/11. When more realistic parameters are assumed, the fall time is found to be even higher, and the collapse may very well not have progressed at all.

Kuttler 2007. This paper investigates a broad spectrum of different scenarios for the collapse of WTC1. Specifically, the "hard top" and "soft top" models are examined, the hard top model assuming the upper section of the building remains intact as it crushes the lower section, while the soft top model assumes the upper section breaks up simultaneously as it breaks up the lower section. Other considerations examined include conservation of energy, conservation of momentum, resistance of the steel support columns, and energy needed to crush concrete. For the purposes set out here, we are mainly interested in two outlined scenarios – one which results in the lowest possible collapse time within reason, and that which gives a more realistic collapse time, assuming all relevant parameters.

In section 1.4.2, it's found that the time of collapse would be approximately 15.95 seconds for the entire building, longer than the actual observed collapse time, and matching the estimate of Cherepanov (2006b). This model assumes variables all biased in favor of a fast collapse, including: The upper section remains intact as it crushes; the collisions between floors are perfectly inelastic; no support at all from the steel columns is considered; no energy is lost due to crushing concrete; no steel is thrown outside the building's perimeter, allowing it all to impart momentum and contribute to crushing. Thus, the lower bound time to collapse is found to be 15.95 seconds.

In section 2.5, more realistic times to collapse are calculated, wherein all of the above-mentioned neglected variables are properly incorporated in to the model. Additionally, a conservative safety factor of 2 is assumed for the columns, the typical factor of safety for buildings (Pluvinage & Sedmak 2009, 178), and approximately that of the Towers' core columns (Rapp 1964; NIST 2005c, 240-41). Although different results are arrived at when these variables are adjusted, Kuttler nonetheless concludes that "fall times of over 25 seconds are expected with reasonable assumptions, yet the observed fall time for the Tower is less than that." He also observes that were a higher safety factor used, the Tower would not collapse completely. For the sake of discussion, we will assume the figure of 25 seconds as the minimum upper bound collapse time predicted here, compared to the observed collapse time of ~14 seconds.

Seffen 2008. This paper outlines a model of progressive collapse similar to the one originally proposed in Bažant & Zhou (2002). A key difference, however, is that the model treats the collapse as a local instability that propagates throughout the whole structure, leading to continuous failures of floors. This contrasts with Bažant & Zhou's approach, instead primarily modelling the impact between the upper and lower sections, and the initial force necessary to trigger collapse. Regardless of these differences, Seffen nonetheless concludes that such instability would lead to a complete collapse of the structure.

In a discussion by Grabbe (2010), numerous flaws are highlighted in Seffen's attempt to simulate the collapse as a simplified 1D model. Those flaws include:

- Like Bažant & Zhou, Seffen assumes the upper section falls virtually in free fall when it impacts the lower section. As was established, however, the rate of fall was less than this, thus the impulse applied to the lower section is smaller than Seffen assumes.
- Also like Bažant & Zhou, Seffen models the upper section as a solid structure which crushes down the lower section completely. However, video of the collapses shows the upper sections breaking up and disintegrating well before the lower sections begin to collapse.
- Videos also show massive horizontal forces at work during the collapses, leading to widespread distribution of dust and debris. Forces such as these are ignored in Seffen's model, treating the downward gravitation force as the only major force during collapse.
- Seffen fails to adequately incorporate conservation of energy and momentum into his model, which would prevent the fast rate of collapse his model predicts.
- Because his model is based on a simplified 1D analysis, it ignores the horizontal extensions of the Towers. This omits the Towers' internal structures, which would act as a resistance to the instabilities the model assumes occurs as the collapse progresses.

Ultimately, the problems in Seffen's model are materially similar to those found in the papers of Bažant *et al*., and thus add little value to the discussion of whether or not collapse progression would result in complete destruction of the Towers.

MacQueen & Szamboti 2009. This paper provides an interesting analysis of the North Tower collapse regarding the initial stage. Specifically, it investigates a primary assumption made in the papers by Bažant *et al.* – that the Tower collapse could only be triggered by "one powerful jolt" (Bažant & Zhou 2002, 369). This "jolt," so to speak, is the initial impulse delivered to the lower section as the upper section falls and impacts it, resulting in an amplified load which then leads to progressive collapse.

As outlined in MacQueen & Szamboti (2009), the main problem is that Bažant *et al*. only *assumed* this impulse occurred, but never actually measured for it. As they point out, if the lower section were to experience a jolt, then the upper section would have to experience one too, in accordance with Newton's Third Law. This in turn would lead to a deceleration of the upper section once it impacted the mass below. An analogy is the example of a hammer striking a nail – the hammer accelerates as it swings down, but once it hits the nail, it no longer moves as fast as it was before doing so. By analyzing high-quality videos of the collapse, the descent of the first nine stories is measured, after which the building section is swallowed up by the resulting dust and debris. The authors find that the upper section fell with an acceleration equal to approximately 71% the rate of gravity continuously for those nine stories. Since the upper section experienced no deceleration – and thus lost no energy – there is no way for it to have imparted energy into the lower section, and thus no way to have produced an amplified load. The assumption, therefore, that the upper section delivered the necessary jolt to the lower section is refuted.

To be sure, this analysis carries some caveats. First, if this rate of acceleration continued for the entire collapse, the whole building would fall in approximately 11 seconds. Since the building actually fell in around 14 seconds, we can say the initial acceleration was not continuous. Thus, we cannot use this analysis to predict an overall collapse time. Second, while this paper assumes the building would suffer a complete collapse, it should not be assumed it proves this would actually occur. As the authors acknowledge, the paper omits several energy sinks, including heat, sound, and vibration produced. These limitations, however, should not take away from the primary conclusion; that the impulse needed to trigger collapse did not happen, thus contradicting the PCM outlined by Bažant *et al*.

Chandler 2010. A similar conclusion to the one drawn in MacQueen & Szamboti (2009) is made in Chandler (2010a). In this paper, the descent of WTC1's upper section is measured, and the same lack of deceleration is found that was reported by MacQueen & Szamboti. Where this paper differs somewhat is that it explores the deeper implications of the constant acceleration, which contradict the supported PCM.

If the upper section descends at a constant acceleration, even one less than the rate of gravity, the resistance it meets would be less than its own weight. Yet according to Newton's Third Law, the force being exerted on the lower section would be exactly the same. Therefore, in this situation the upper section would exert *less* force on the lower section than its normal static load. In turn, this means the acceleration is the *result*, not the cause, of the lower section's destruction, since the upper section cannot possibly be providing the force needed to collapse the lower section. Since the PCM is predicated on the notion that the upper section's descent is what triggers the progressive collapse, the constant acceleration of the building's top section directly contradicts the model, at least at the very early stages of collapse.

Denny 2010. This paper sets out to examine the rate of fall of the Towers, concluding that when buildings collapse through pancaking, with one floor falling on to the next, the total fall time "is found to be not much slower than freefall" (Denny 2010, 943). While this paper is instructive in laying out the physics of a high-rise collapse, it utilizes several questionable assumptions that undermine the thesis it sets out to demonstrate.

- First, similar to Seffen (2008), the paper simulates the collapse as a simplified 1D model. As we saw in our discussion of Seffen, this removes any sort of horizontal forces or resistance during collapse, and thus will reduce the collapse time.
- The paper assumes the collisions between floors are totally inelastic. This is similar to the approach of other studies discussed here, but does not simulate the collapse realistically by means of the time and energy needed in collapsing the floors.
- The paper also ignores any resistance from the columns, instead only considering the floors pancaking.
- The author assumes no loss of mass during floors collapsing. Again, this assumption was also made by others, but is in contrast to the Tower collapses that were actually observed, wherein a large portion of debris was either pulverized or thrown outside the buildings' footprints.
- Omitted from the analysis is air resistance, either through aerodynamic drag or the pressure built up from the collapsing floors.

With these variables factored in to the model, Denny concludes the collapse time will be about 50% greater than free fall.

Again, many of the assumptions made here are questionable, and the conclusion the author reaches, that a pancaking collapse will be not much slower than free fall, appears hyperbolic. It is difficult to understand how a fall exceeding free fall by 50% qualifies as "not much slower," and no explanation is ever given as to exactly what this means. To be fair, the simplifications assumed in the model are fully acknowledged by the author. And yet, far from demonstrating a pancake collapse will be "only slightly greater than that of freefall" (Denny 2010, 944), the author appears only to have demonstrated what we could reasonably expect given the most *favorable* conditions for a fast collapse. As such, the paper, while instructive, offers little to no support that the PCM is a viable model for the collapse of the Towers on September 11th.

Le & Bažant 2011. The lack of deceleration in the upper section of WTC1 during the initial stage of collapse is certainly regarded as anomalous. Le & Bažant (2011) attempt to explain this anomaly by arguing that the initial velocity drop did indeed occur, but was too small to be detected in videos of the collapse. Although not stated outright, the authors are likely responding to the points made in MacQueen & Szamboti (2009) and Chandler (2010a). According to them,

> [A] new objection, pertaining to the smoothness of the observed motion history of the tower top, has been raised and disseminated on the internet. […] Here it is shown that the velocity drop must have been three orders of magnitudes smaller than the error of an amateur video, and thus undetectable.

However, in Szuladziński *et al*. (2013, 121-23) and Jones *et al*. (2016, 25), significant flaws are highlighted in this line of reasoning, summarized as follows:

- Le & Bažant repeat the error found in Bažant & Verdure (2007) that the mass of the upper section was 54.18×10^6 kg. However, as was pointed out earlier, the mass was in fact only 33.18×10^6 kg, over one third lower than their estimate.
- They also repeat the error common to all of Bažant *et al*.'s papers, that the upper section fell essentially in free fall to impact the lower section. Again, actual measurements show the fall was closer to 2/3 of free fall, thus reducing the velocity and overall kinetic energy involved in the collapse.
- Le & Bažant erroneously give the impacted floor mass as 0.627×10^6 kg. In an earlier paper, however, Bažant *et al*. (2008, 905) correctly give the mass as 3.87×10^6 kg. Correcting this error increases their claimed conservation-of-momentum velocity loss of 1.1% to 7.1%.

In addition to these numerical errors, Le & Bažant's assertions contradict real-world physical observations of similar phenomena. Building demolitions carried out in France, in which no explosives are used, involve dropping the structure's upper section on to the lower section. When similar measurements are done for the upper section's descent, a clear deceleration and velocity loss is recorded (Chandler 2010b).

Because this paper largely repeats the errors of previous analyses by Bažant *et al*., it adds little to the discussion, and thus offers no real support for the PCM.

Němec, Juráňová, Ševčík, Frantík, & Vlk 2012. In this paper, the authors investigate the collapse of the Twin Towers from the viewpoint of the basic laws of mechanics, while deriving probable collapse-time estimates based on parameter variations. The collapses are analyzed through a computer simulation, wherein two independent programs are utilized. The results are then compared with assumptions previously utilized by Kuttler – envisioning the collapses occurring with no structural support from columns and no elastic resistance from the floors.

By employing their two programs and comparing the results to that of Kuttler, the authors find the probable lowest collapse time to be approximately 15.85 seconds. They note that while these methods utilized different approaches, the results yielded comparatively similar solutions. They also note that when column resistance is properly incorporated into the model, the collapse times will naturally be even longer, and that possibly "the fall could even cease before the whole building destructs."

Szuladziński 2012. This paper looks at the collapse of the North Tower, estimating the time of fall and critiquing the commonly held PCM as an explanation for the Tower collapses (referred to as "pancaking" in this case). The estimation is, as other studies discussed have done, biased in favor of producing a fast collapse, assuming supports which provide negligible resistance, such as perfectly frangible columns.

The paper envisions the collapse occurring through three different scenarios. Scenario one envisions a collapse in which the interactions between structural components remain unchanged during collapse progression. Scenario two envisions a similar process, only here the additional mass of the building's roof is assumed to be larger, and the structure's shell is considered inactive due to damage. Scenario three simulates the most favorable conditions for a fast collapse, envisioning perfectly frangible columns, or columns reduced to 1/10 their original strength.

Scenarios one and two result is collapse times of 30.19 and 23.53 seconds, respectively. These represent more realistic upper bound times to collapse. The mean average of these times works out to approximately ~26.9, which is well in line with Kuttler's observation that the collapse realistically should have exceeded 25 seconds. Scenario three, when adjusted to take account of sequential collisions between floors, results in a collapse time of 15.33 seconds. Again, this lines up well with the observations of Ross, Kuttler, Cherepanov, and Němec *et al*., who found the lowest possible collapse time to be slightly higher than 15 seconds. As Szuladziński concludes, "the pancaking mode is not a realistic proposition, as the calculated fall time becomes much too long."

Also like Kuttler, Szuladziński uses a safety factor of approximately 2 (1.9 to be exact), which as noted before is a conservative figure. He argues the factor was more than likely higher, given that wind-loading was the dominant load factor of the design, and September 11th was not a particularly windy day (Eagar & Musso 2001).

When the safety factor is higher, he finds the collapse would most likely be arrested.

Szuladziński, Szamboti, & Johns 2013. This paper serves as a critical critique of the oft cited PCM outlined in Bažant *et al*.'s various papers. Noting these studies promote concepts that, while popular and still circulating in the engineering community, rely on false data and incorrect assumptions regarding the mass, velocity, and columns resistance during WTC1's collapse. Though not an exhaustive look into how the buildings collapsed, it serves as a useful tool in determining how the Towers *could not* have collapsed, and thus allows for a possibly more elaborate and coherent model explaining how the buildings actually came down.

While exposing the various flaws in Bažant *et al*.'s proposed PCM – noted previously; the incorrect mass, velocity, and column strength – the authors establish that when the relevant parameters are properly calculated, the collapse would be arrested within the first one to two stories of the fall. They also reaffirm the conclusion drawn in Szuladziński (2012) – that were the collapse allowed to progressive beyond the first few stories, the overall collapse would take approximately 15.3 seconds, assuming variables biased in favor of the shortest possible fall time. When all relevant parameters are properly accounted for, the authors conclude that "[t]his removes the [Progressive Column Failure] mode […] as a viable hypothesis of collapse."

Němec, Trcala, Vala, & Vaněčková 2018. This analysis provides a detailed study of the Towers' collapse, investigating the theoretical upper limit speed of collapse and acceleration. In essence, this paper serves as an updated version of the analysis in Němec *et al*. (2012), and arrives at very similar conclusions. By assuming several simplifications via neglecting certain collapse variables, the authors are able to obtain figures for the upper limit of the speed and acceleration of the fall.

In their calculations, the authors make similar assumptions to that of Cherepanov (2006b), whereby several variables are neglected from the model. These include resistance from the columns, air resistance, loss of mass through floor collisions, and elastic responses from the floors. Also like Cherepanov, the authors find that when such variables are neglected and the collapse is slowed only by inertia, the overall acceleration of the collapse will be only 1/3 that of gravity. This results in a collapse time of approximately 15.82 seconds, very close the Cherepanov's figure of 15.95, and virtually the same as the 15.85 figure arrived at in Němec *et al*. (2012).

Modifying their assumptions to take account of variables such as the resistance from the floor impacts and the loss of mass through collisions, the authors then find the more realistic upper bound collapse will only be 1/5 of gravity, and the time of fall will be approximately 20.42 seconds. Again, these figures are consistent with Cherepanov's findings, who made very similar assumptions. Important to note, however, is that this is a conservative estimate, as they've still neglected the resistance imposed by the columns. When this crucial factor is accounted for, the authors find the fall could be arrested before total collapse, in line with the findings of Ross, Kuttler, and Szuladziński. Regardless, because the observed fall time of the Towers contradicts all of these estimates, the authors conclude that "the mechanism of the collapses must be different from" the PCM assumed by Bažant *et al*. and others.

Schneider 2019. In this conference paper, Schneider (2019) analyzes the collapse of the North Tower within the framework of critiquing Bažant *et al*.'s PCM. The approach Schneider takes is to assume that the assumptions outlined in Bažant *et al*.'s various papers are correct, with regard to the initial fall of the Tower's upper section. However, he then goes on to estimate the upward resistance force of the lower section, and finds serious flaws with the conclusion that the collapse was guaranteed to progress.

Primarily analyzing the collapse from the first 4.6 seconds up until 7.7 seconds, he finds that the upward resistance force of the lower section would have been 500 MN (meganewtons). However, the measured resistance force found is only 66 MN – around 13% of the force that should have been there. That roughly only 1/10 of the resistance was present during the early stage of collapse is consistent with Chandler's observation that "close to 90% of the strength of the lower section of the building must have been eliminated" (Chandler 2010a, 10). Schneider also finds that estimating the resistance even after 7.7 seconds, the lower section would likely have arrested the collapse. As he concludes, "the sometimes expressed belief that the building structure was a priori too weak to arrest the collapse after it had begun is false."

Le & Bažant 2022. The most recent discussion of the WTC progressive collapse, this paper is broken into two sections. The first section outlines a mathematical model to explain the fall of the Towers through progressive collapse, and the second presents a computational model for the collapse of reinforced concrete (RC) buildings. While the second section is a useful discussion of the mechanics and vulnerability of RC framed structures, even providing insight into how progressive collapses in such structures can potentially be avoided, it is the first section we are primarily concerned with. While presented as offering a model that "[agrees] well with different observations of the collapse process," the first half of this paper is, in fact, based on flawed assumptions we have already discussed here.

What is quickly apparent is that Le & Bažant's model of the WTC collapse is based upon previous studies by Bažant *et al*. which, as we've seen, rely on many flawed assumptions and miscalculations. Regardless of the quantitative detail employed in the modelling, there is no indication Le & Bažant took account of any critiques of the work upon which their model is based (e.g., Szuladziński *et al*. 2013, Schneider 2019). Indeed, the differential equations upon which their model is based turn out to be derived from an earlier model outlined in Le & Bažant (2017), which in turn refers readers to previous work which we have already found to be highly problematic (i.e., Bažant & Zhou 2002, Bažant & Verdure 2007, Bažant *et al*. 2008). The flaws of that study are numerous, and are critiqued in a whitepaper by Korol & Szamboti (2017).

Other Studies. Three additional studies are worth considering in this discussion. The first two are whitepapers published by Mitteldorf (2018) and Chandler (2019). The paper by Mitteldorf assumes the collapse is slowed only by inertia, but assumes no support from the columns and inelastic collisions between floors. Essentially, the collapse is modelled to simulate the most favorable conditions for a fast fall, similar to previously discussed studies. The analysis finds the lowest possible collapse time to be approximately 16 seconds. He also notes that neglecting the continuous mass distribution assumed in his calculations could result in the collapse being one second shorter, around 15 seconds instead.

The paper by Chandler makes similar assumptions, although models the successive collapse of each floor in a spreadsheet. Again, no support from the columns is assumed, and the floor collisions are assumed to be totally inelastic. The result is a collapse estimated to take approximately 14.92 seconds. This is slightly shorter than other estimates discussed, but still in the same general ballpark, and still slightly higher than the estimated time of fall for the Towers. Although neither of these studies have been subjected to peer-review, their conclusions are well in line with the results found in studies which have been published in proper peer-reviewed venues, and thus worthy of consideration.

A third study worth considering was published by Korol *et al*. (2011), which offers indirect support for the idea that the PCM is inapplicable for the collapse of the Towers. The authors simulate the collapse mechanics of a series of hypothetical ten-story structures. The results were that in 90 percent of the examined cases, the collapse was arrested. For the remaining 10 percent, the fall times exceeded free fall by 57 to 228%. Again, these results are well in line with the conclusions reached by other researchers; had the Towers truly fallen via PCM, the collapses would have taken far longer than observed, or perhaps resulted in the collapse being arrested.

III. DATA INTERPRETATION

To fully appreciate the disparity between the observed features of the Towers' collapses and the many detailed measurements of what realistically should have been observed, we can consider the average accelerations predicted by these measurements, and how much the fall times exceed a free fall from the Towers' heights. The time it would take for an object to reach the ground from the height of either Tower would be 9.2 seconds. The actual time it took them to fall was approximately 14 seconds. Since we can't see the full collapses clearly, due to the heavy amount of dust and debris, we are unable to accurately track the exact rate of acceleration at every point. Thus, the best we can do is try to estimate the average acceleration.

The calculation to determine average acceleration is $a = (2d/t^2) - (2v/t)$, where d = distance (in feet), t = time (in seconds), and v = velocity. Since we are assuming the buildings start at rest, we can discard the second part of the equation and shorten it to simply $a = 2d/t^2$. With a fall time of 14 seconds, this means an average acceleration of approximately 13.95 ft/s^2. A 14 second fall time also means the fall exceeded a free fall time by approximately 52%. Of the estimates which calculated the shortest possible collapse time, based on conditions biased in favor of a fast collapse, the lowest was that of Denny (2010), whose estimates of a fall exceeding free fall by 50% results in a collapse time of 13.8 seconds. The highest was Mitteldorf (2018), at 16 seconds. All the rest fit comfortably in the middle of these estimates.

The shortest time to collapse, based on more realistic parameters, was estimated by Ross (2006b) to be 20.02 seconds. Note that this was still a conservative estimate, neglecting the support from the columns. The highest time estimated was by Szuladziński (2012), at 30.19 seconds. To be sure, there is more disparity between the estimates of realistic collapse times than the shortest times, but this is not particularly surprising. The estimates of the shortest possible fall times used very consistent estimates, visualizing the collapses based on little to no resistance from the columns, and perfectly inelastic collisions between floors. Given that these scenarios assume the falls are essentially only slowed by inertia, it is not particularly surprising that we find them consistent with one another. Calculating realistic fall times, by contrast, is understandably more difficult, as such a collapse would be very chaotic, and thus unpredictable at various stages. The difference in parameters envisioned, as a means of trying to simulate the collapses based on every realistic scenario, will naturally result in varying fall times.

Of all these estimates, the shortest, 13.8 seconds, and the longest, 30.19 seconds, gives us fall times exceeding free fall by 50 and 228%, which fits remarkably well with Korol *et al.*'s (2011) observation that progressive collapses that are allowed to progress will exceed free fall by 57 to 228%. Yet with collapses that lasted in the range of the shortest estimated times, and possibly even slightly less, the PCM appears to be an untenable scenario for the fall of the Twin Towers.

Table 1: Estimates of shortest possible collapse times

Collapse Model	Fall Time (seconds)	Average Acceleration (ft/s^2)	Exceeds Free Fall Time
Actual WTC Collapse	14	13.95	52%
Cherepanov	15.95	10.75	73%
Ross	15.44	11.47	67%
Kuttler	15.95	10.75	73%
Denny	13.8	14.36	50%
Němec *et al.* (a)	15.85	10.84	72%
Němec *et al.* (b)	15.82	10.93	72%
Szuladziński	15.33	11.64	66%
Mitteldorf	16	10.68	73%
Chandler	14.92	12.29	62%
Mean Average	**15.45**	**11.52**	**67%**

Table 2: Estimates of realistic collapse times

Collapse Model	Fall Time (seconds)	Average Acceleration (ft/s^2)	Exceeds Free Fall Time
Cherepanov	20.63	6.42	124%
Ross	20.02	6.82	117%
Kuttler	25	4.37	171%
Němec *et al.*	20.42	6.56	121%
Szuladziński (a)	23.53	4.94	155%
Szuladziński (b)	30.19	3	228%
Mean Average	**23.29**	**5.35**	**152%**

IV. CONCLUSIONS

Based on the data reviewed here, the author concludes that the PCM, first outlined by Bažant & Zhou (2002) and endorsed by NIST, is not a viable scenario for the collapse of the Twin Towers. A review of the relevant literature published in the two decades since the attacks reveals analyses directly contradicting progressive collapse as the primary mechanism which led to the total destruction of both buildings. Both the observed acceleration and time of collapse are at odds with the majority of studies which have taken an in-depth analysis of each, and several of them reach the conclusion that the collapse likely should not have totally progressed at all.

The results of this analysis also lead to troubling implications. Although the PCM is still widely regarded as the most viable explanation of total collapse, the amount of literature providing technical support for it is actually quite small, compared to that devoted to detailing the factors which initiated the collapse. Indeed, according to a meta-analysis by Eastman & Cole (2013), the technical literature discussing the WTC collapse, published in the decade after 9/11, showed no consensus with regards to explaining the total destruction of the Twin Towers. Ten years later, the situation appears no better.

As we saw, the most significant example of this inadequacy is the NIST investigation. The mandate of NIST was only to investigate the conditions which led to collapse initiation, but it is unclear why examination of the total collapse was evidently deemed outside the scope of inquiry. The only support available at the time was the analysis of Bažant & Zhou (2002), but there is no indication NIST ever independently evaluated their results. This is especially problematic because, as we saw, several of NIST's estimates actually contradict points made by Bažant & Zhou. And considering the ease with which many independent researchers have been able to evaluate their results, it is unclear why NIST did not do the same.

Investigating ways in which building collapses can be prevented is very important, and NIST is commendable for contributing to this broad ongoing study. Yet equally important, in this author's view, is to find ways to minimize the damage caused by collapsing buildings in the event they do initiate. Indeed, as the Federal Emergency Management Agency recommended in their initial WTC investigation, "Studies should be conducted to determine […] whether there are feasible design and construction features that would permit such buildings to arrest or limit collapse, once it began" (FEMA 2002a, 5).

The review of relevant literature here is not directly concerned with how the buildings collapsed, but rather how they could not have collapsed. A progressive collapse, in which gravity is the primary force driving the destruction, is not supported as a viable model for the Towers in the majority of studies we have considered. Most have found the lowest possible fall time to be in the range of 15 seconds, yet the actual collapses were in this range, and possibly even below it. As we've seen, such a low time is only attainable when wholly unrealistic assumptions are used. Based on the estimates considered here, we can safely assume the lowest time to collapse would have been approximately 15 seconds, with a margin of error of ± 1 second. And although there is some disparity in regards to what more realistically should have been observed, this author finds that collapse times of over 20 seconds are more reasonable expectations when relevant factors are properly accounted for.

The PCM is, to quote Szuladziński (2012), indeed not a viable model, as the collapse times become much too long. Nor should we assume, contrary to the assertions of Bažant *et al*., that once the collapse began it would necessarily have continued all the way to the ground. As the various studies we've considered make clear, the collapse could very well have been arrested before total collapse took place. Due to the significant errors exposed in the PCM, this author calls for critical re-evaluation of the collapse of the Twin Towers, in the hope that more rigorous, detailed, and coherent models are developed in order to accurately explain their destruction. Which, in turn, will lead to a better understanding of how building collapses can be prevented in the future, in the hopes of saving many lives.

APPENDIX A. REAL-WORLD EXAMPLES

High-rise collapses of any kind are rare, especially those initiated by fire. According to the Federal Emergency Management Agency, "prior to September 11, 2001, no protected steel frame buildings had been known to collapse due to fire" (FEMA 2002b, 9). Likewise, according to Glover (2002, 97), before 9/11, "No major high-rise building [had] ever collapsed from fire." While fortunate in terms of preserving life and reducing property damage, this fact makes comparison to other real-world progressive collapses difficult for the purposes set out in this paper. Regardless, an analysis of limited examples can offer at least some insight into the discussion of what can be expected when a structure succumbs to a collapse primarily driven by gravity.

To the best of this author's knowledge, only two such structures have collapsed due to this process in a similar manner: the Faculty of Architecture Building in the Netherlands in 2008, and the Plasco Building in Iran in 2017. The choice to examine these structures is motivated by four factors:

- Both buildings were "high-rises," by the standard definition of exceeding 100 feet in height (Craighead 2009, 24).
- Like the Towers, both buildings were primarily steel-framed.
- Both buildings are said to have collapsed due to fire.
- Both succumbed to a top-down progressive collapse.

To be sure, comparing these structures to the Towers carries noteworthy caveats. Both were far different in construction, and in the case of the Faculty Building, it only suffered a partial collapse of one section. But given that the mode of destruction for these structures is said to apply to the Towers, the author contends there are enough surface similarities to warrant comparison, if only limited. As one investigation even acknowledges, "the structural system of the Plasco Tower has considerable similarity to that of the WTC Towers" (Yarlagadda *et al*. 2018, 408).

Again, the point is not to examine the initiation of collapse, but rather what was observed as the collapse progressed. In this regard, we are interested in the time it took these buildings to collapse, and how those times compare to the calculated time of free fall. Several videos exist of both buildings' collapses, so examining these data points is fairly simple.*

The highest point of the Faculty Building was 183 feet. Again, while this wasn't a total collapse, as only one section fell, the section did so in a top-down fashion, just like the Towers are said to have. The section collapsed in approximately 9 seconds. A free fall from that height would have taken approximately 3.3 seconds. Therefore, the collapsed section exceeded free fall by 172%, and its average acceleration was 4.51 ft/s^2. The Plasco Building was 138 feet tall. It collapsed completely in approximately 15 seconds. A free fall collapse would have taken approximately 2.9 seconds. Such a collapse would therefore have exceeded free fall by 417%, and the average acceleration was approximately 1.22 ft/s^2. Important to note, however, is that the last portion of the building that appears to have fallen was part of the exterior wall. The interior of the building (i.e., the floors) appears to have fallen in approximately 10 seconds. If we revise our estimates with this figure, we instead get a coll-

* Faculty Building: https://youtu.be/c1SF3K5PaWI.
Plasco Building: https://youtu.be/_MgJTa7SDaY.

apse exceeding free fall by 244%, and an average acceleration of 2.76 ft/s^2.

These are, of course, limited examples, and no deep results should be claimed from such observations. Yet it is interesting to note how these two cases are in line with the calculated estimates of what we should expect from actual gravity-driven progressive collapses. Considering these are, as of writing this, the only other examples of high-rise, top-down progressive collapses due to fire, it may be instructive to consider them in future evaluations, and those include any further study of the WTC collapses.

REFERENCES

Anonymous and F. Legge (2009), "Falsifiability and the NIST WTC Report: A Study in Theoretical Adequacy," *Journal of 9/11 Studies* 29. Online at http://www.journalof911studies.com.

Bažant, Z., J.-L. Lee, F. Greening, and D. Benson (2008), "What Did and Did Not Cause Collapse of World Trade Center Twin Towers in New York?," *Journal of Engineering Mechanics* 134(10): 892-906.

Bažant, Z., and M. Verdure (2007), "Mechanics of Progressive Collapse: Learning from World Trade Center and Building Demolitions," *Journal of Engineering Mechanics* 133(3): 308-319.

Bažant, Z., and Y. Zhou (2002), "Why Did the World Trade Center Collapse? – Simple Analysis," *Journal of Engineering Mechanics* 128(1): 2-6. Addendum 128(3): 369-370.

Chandler, D. (2010a), "Destruction of the World Trade Center North Tower and Fundamental Physics," *Journal of 9/11 Studies* 28. Online at http://www.journalof911studies.com.

— (2010b) "What a Gravity-Driven Demolition Looks Like." Online at https://www.youtube.com/watch?v=NiHeCjZlkr8.

— (2019), "Idealized Pancake Theory Collapse Time." Online at http://www.scientistsfor911truth.com/wp-content/uploads/2019/01/IdealizedPancakeCollapseCalcs.pdf.

Cherepanov, G. (2005), "September 11 and Fracture Mechanics – A Retrospective," *International Journal of Fracture* 132: L25-L26.

— (2006a), "On the Collapse of the World Trade Center Towers on September 11, 2001," *Вестник СамГ – Естественнонаучная серия* 2(42): 74-91.

— (2006b), "Mechanics of the WTC collapse," *International Journal of Fracture* 141: 287-289.

— (2008), "Collapse of Towers as Applied to September 11 Events," *Material Science* 44(4): 489-499.

Cherepanov, G., and I. Esparragoza (2007), "Progressive Collapse of Towers: The Resistance Effect," *International Journal of Fracture* 143: 203-206.

Craighead, G. (2009), *High-Rise Security and Fire Life Safety*, 3rd ed., New York: Elsevier.

Denny, M. (2010), "How Fast Does a Building Fall?," *European Journal of Physics* 31(4): 943-948.

Douglas, E. (2006), "The NIST WTC Investigation – How Real Was The Simulation?," *Journal of 9/11 Studies* 6. Online at http://www.journalof911studies.com.

Eagar, T., and C. Musso (2001), "Why Did the World Trade Center Collapse? Science, Engineering, and Speculation," *JOM* 53(12): 8-11. Online at https://www.tms.org/pubs/journals/jom/0112/eagar/eagar-0112.html.

Eastman, T., and J. Cole (2013), "WTC Destruction: An Analysis of Peer Reviewed Technical Literature 2001—2012," *Journal of 9/11 Studies* 37. Online at http://www.journalof911studies.com.

FEMA (2002a), "World Trade Center Building Performance Study (Chapter 8)." Online at https://www.fema.gov/pdf/library/fema403_ch8.pdf

— (2002b) "World Trade Center Building Performance Study (Appendix A)." Online at https://www.fema.gov/pdf/library/fema403_apa.pdf.

Glover, N. (2002), "Collapse Lessons," *Fire Engineering*, pp. 97-104.

Grabbe, C. (2010), "Discussion of 'Progressive Collapse of the World Trade Center: Simple Analysis' by K.A. Seffen," *Journal of Engineering Mechanics* 136(4): 538-539.

Greening, F. (2006), "To whom it may concern," *Journal of 9/11 Studies* 2. Online at http://www.journalof911studies.com.

Jones, S., R. Korol, A. Szamboti, and T. Walter (2016), "15 Years Later: On the Physics of High-Rise Building Collapses," *Europhysics News* 47(4): 21-26.

Korol, R., K. Sivakumaran, and F. Greening (2011), "Collapse Time Analysis of Multi-Story Structural Steel Buildings," *The Open Civil Engineering Journal* 5: 25-35.

Korol, R., and T. Szamboti (2017), "A Response from the 'Lay Critics' Regarding 'Mechanics-Based Mathematical Studies Proving Spontaneity of Post-Impact WTC Towers Collapse.'" Online at https://www.ae911truth.org.

Kuttler, K. (2007), "Collapse Time Calculations for WTC 1," *Journal of 9/11 Studies*. Online at http://www.journalof911studies.com.

Le, J.-L., and Z. Bažant (2011), "Why the Observed Motion History of World Trade Center Towers Is Smooth," *Journal of Engineering Mechanics* 137(1): 82-84.

— (2017), "Mechanics-Based Mathematical Studies Proving Spontaneity of Post-Impact WTC Towers Collapse" *Europhysics News* 48(1): 18-23.

— (2022), "Spontaneous Collapse Mechanism of World Trade Center Twin Towers and Progressive Collapse in General," *Journal of Structural Engineering* 148(6).

MacQueen, G., and T. Szamboti (2009), "The Missing Jolt: A Simple Refutation of the NIST-Bazant Collapse Hypothesis," *Journal of 9/11 Studies* 24. Online at http://www.journalof911studies.com.

McIlvaine, B., B. Doyle, S. Jones, K. Ryan, R. Gage, and F. Legge (2007), "9/11 Family Members and Scholars: Request for Correction Submitted to NIST," *Journal of 9/11 Studies* 12. Online at http://www.journalof911studies.com.

Mitteldorf, J. (2018), "How Did the Three WTC Towers Fall? A Minimum Time for 'Pancaking' Collapse." Online at https://scientistsfor911truth.com/wp-content/uploads/2018/12/Min_Time_for_Pancaking.pdf.

Němec, I., M. Juráňová, I. Ševčík, P. Frantík, and Z. Vlk (2012), "Dynamics of Collapse of a High Building," *Journal of Mechanics Engineering and Automation* 2: 349-354.

Němec, I., M. Trcala, J. Vala, and A. Vaněčková (2018), "A Contribution to Analysis of Collapse of High-Rise Building Inspired by the Collapses of WTC1 and WTC2: Derivation of Simple Formulas for Collapse Upper Speed and Acceleration," *Journal of Applied Mathematics and Physics* 6: 2666-2680.

NIST (2005a), NCSTAR 1. Online at https://www.nist.gov/el/final-reports-nist-world-trade-center-disaster-investigation.

— (2005b), NCSTAR 1-3. Online at https://www.nist.gov/el/final-reports-nist-world-trade-center-disaster-investigation.

— (2005c), NCSTAR 1-6. Online at https://www.nist.gov/el/final-reports-nist-world-trade-center-disaster-investigation.

— (2005d), NCSTAR 1-6D. Online at https://www.nist.gov/el/final-reports-nist-world-trade-center-disaster-investigation.

— (2011), "Questions and Answers about the NIST WTC Towers Investigation." Online at https://www.nist.gov/world-trade-center-investigation/study-faqs/wtc-towers-investigation.

Pluvinage, G., and A. Sedmak (2009), *Security and Reliability of Damaged Structures and Defective Materials*, Netherlands: Springer.

Rapp, R. (1964), "The World Trade Center: An Architectural and Engineering Milestone," *Contemporary Steel Design* 1(4).

Ross, G. (2006a), "Momentum Transfer Analysis of the Collapse of the Upper Storeys of WTC 1," *Journal of 9/11 Studies* 1. Online at http://www.journalof911studies.com.

— (2006b), "Reply to Dr. Greening," *Journal of 9/11 Studies* 2. Online at http://www.journalof911studies.com.

Schneider, A. (2019), "The Structural Dynamics of the World Trade Center Catastrophe," *IABSE New York City, The Evolving Metropolis, Congress Report* 114: 2151-2156. Online at https://arxiv.org/abs/1910.10801.

Seffen, K. (2008), "Progressive Collapse of the World Trade Center: Simple Analysis," *Journal of Engineering Mechanics* 132(2): 125-132.

Szuladziński, G. (2012), "Temporal Considerations in Collapse of WTC Towers," *International Journal of Structural Engineering* 3(3): 189-207.

Szuladziński, G., A. Szamboti, and R. Johns (2013), "Some Misunderstandings Related to WTC Collapse Analysis," *International Journal of Protective Structures* 4(2): 117-126.

Taylor, A. (2022), "Review of Literature Regarding Progressive Collapse of WTC Twin Towers – A Call for Re-evaluation," *International Journal of Engineering and Techniques* 8(2): 45-54.

Urich, G. (2007), "Analysis of the Mass and Potential Energy of World Trade Center Tower 1," *Journal of 9/11 Studies* 18. Online at http://www.journalof911studies.com.

Yarlagadda, T., H. Hajiloo, L. Jiang, M. Green, and A. Usmani (2018), "Preliminary Modelling of Plasco Tower Collapse," *International Journal of High-Rise Buildings* 7(4): 397-408.