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The collapse of WTC 7: A re-examination of the “simple analysis” approach

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ABSTRACT

Although the events of that tragic day happened 14 years ago, there remain nagging questions of why the 47 storey WTC 7 steel framed structure collapsed, when it was NOT hit by an airplane. We will review the official rationale of how the collapse events started, and why, in our opinion, the explanation is judged to be wrong. Then, we will proceed with another scenario that says “Okay – let’s assume that the two critical storeys did sustain extremely hot fires, so much so that 2/3rds of their columns totally lost axial resistance capability”. We then proceed to employ Newton’s laws to inquire whether there was sufficient gravitational potential energy due to live and dead loadings in upper and lower floors to overcome the resistance offered by the remaining columns, together with floor slabs known to have been pulverized to reduced particle sizes by surface to surface crushing. Our conclusion suggests that Newton’s laws of motion and energy conservation considerations would have had to have been violated to explain that building’s total collapse within a debris pile several storeys high.

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1. Introduction

Despite the many years that have passed since the horrendous events of 9/11, questions still remain about why such robust, overly-designed and well constructed buildings collapsed on that fateful day in 2001. Of course, airplane strikes and raging fires that purportedly caused the demise of WTC 1 and 2 are one thing, but in the case of the 47 story Building 7, only fires can be blamed. And yet, as engineers we design buildings, steel or reinforced concrete, to resistant such extreme loadings.

Our purpose is to re-examine the evidence and the assumptions employed by others who claim that fires alone can explain why WTC 7 collapsed completely and symmetrically into its own footprint. The official narrative (NIST, 2008a) is that the spread of hot fires from work station to work station, initiated by incendiary debris that catapulted a distance of approximately 100 m, from a collapsing twin tower (WTC 1), was responsible. Their claim is that heavy debris amongst the vast amount of fine dust, broke windows and severed 7 perimeter columns principally on the south face of Building 7. The consequence of that event was that flammable materials within office areas were ignited at various floor levels and subsequently generated sufficient heat in a process known as flash-over, that extended the burning times for nearly 6 hours in some floor levels. According to the government agency known as the National Institute of Standards and Technology (NIST) especially vulnerable was the 13th floor where a girder to interior column connection failed (NIST, 2008b). The hypothesis was that core column 79 lost floor level support, then buckled, resulting in a cascade of failures propagating horizontally. Without an adequate structural support system for the upper block of stories, progressive collapse by gravitational forces alone is claimed to have followed, and therefore was responsible for the outcome – a debris pile a few storeys high, largely within its footprint.

Our recent article (Korol et al., 2015) questions the likelihood that such a scenario could have taken place. However, that said, it may be that some other mechanism of failure may have been at play during this time which NIST may not have recognized. The issue then becomes – what is the probability that the structure would have succumbed to total collapse employing some other scenario of initial failure and subsequent events leading

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to total progressive collapse? Our approach is one which aims to deliberately avoid answering that question, but rather addresses the very issue at the heart of the matter – i.e. that there was sufficient resistance built into the structure that regardless of a local failure, the structure should not have suffered a total collapse.

2. A Bit of History

Very shortly after the collapse of the twin towers, Bazant and Zhou (2002) published their paper "Why did the World Trade Center collapse? Simple analysis" in the Journal of Engineering Mechanics. Our title highlights "simple analysis" because it is also in that vein that we wish to make the case that a sophisticated analysis is not a prerequisite for verifying or not the rationale for supporting the hypothesis of a gravitational driven collapse. We shall argue that quite the contrary is in fact the case.

Much has been written about whether the gravity driven collapse event itself could have taken place at the speed which was recorded by video cameras. Some analyses claim that the motion of WTC 7 during at least part of the collapse event was too rapid to have happened without the use of explosives (Griffin, 2010) while NIST (2008) and Dunbar and Regan (2006) refute such claims. While such approaches may utilize Newton's laws of motion correctly, they suffer from an inherent weakness – namely, underestimation of the built-in resistance of a steel-framed structure that has floor systems consisting of materials, in particular concrete slabs possessing shrinkage steel which when tallied together will absorb copious amounts of energy. When accounting for such energy absorption potential that is possessed by a structure poised to tumble down into a pile of rubble, we are compelled to ask whether the gravitational potential energy of such a structure will exceed the inherent dissipative capacity. It is in this context about which we wish to make the case of whether there was the likelihood of a total collapse of Building 7 following fires that would have seriously weakened the gravity support system in storeys known to have been compromised because of weakened conditions due to fire.

3. Basic Assumptions

Several floors in WTC 7 were known to have been subject to hot fires during late morning and the afternoon of Sept, 11th, 2001. The most intense of these are reported to have been on floors 12 and 13 (NIST, 2008b). It is unknown whether intense heat occurred simultaneously or if at essentially the same time. We will make the assumption that columns on both floors were compromised at the same time, a conservative estimate. As well, we will ignore the energy associated with floor beams and girders bending or twisting, or steel connections failing, or indeed of filing cabinets, inside partitions, tables and chairs being crushed. Our focus will only be on the 82 steel columns existing from above the 7th floor level, up to the 44th, with 70 in the top 3 storeys, together with pulverizing portions of concrete slabs that would have been subject to crush forces due to steel floor members impacting the floors below.

4. Energy Absorption Capacity of Columns

In their "rapid communication" paper to the Journal of Engineering Mechanics, Bazant and Zhou (2002) state unequivocally in the abstract "The analysis shows that if prolonged heating caused the majority of columns of a single floor to lose their load carrying capacity, the whole tower was doomed". Since they were not privy to the details of the columns at the time of their original version (2 days following the 9/11 events), such a statement without evidence was indeed surprising. While the context pertained to one or both of the twin towers, the "simple analysis" could, and was used by NIST in their final report (2008b) in analyzing the rapid progressive collapse of WTC 7. Unfortunately, despite the many years following 9/11, there was virtually no effort made to postulate a collapse scenario that employed basic principles of mechanics and which considered the real energy dissipative capacity inherent in the columns under the circumstances that occurred, i.e. raging fires that would potentially jeopardize the ability of some structural elements to sustain reasonable intensities of service loading. The Bazant and Zhou model, which formed the basis for collapse of a typical column, assumed plastic hinges at the top, bottom and at mid-height. This may appear at first blink to be a collapse mechanism that over-estimates the energy absorbed during post-buckling because of presumed fixity at floor and ceiling junctions with cross members. However, such a model does not account for the non-recoverable energy associated with axial compression – the attribute about which columns are meant to resist.

At McMaster, a series of experiments was undertaken on H-shaped columns of ductile aluminum possessing stress-strain properties similar to mild structural steel, and which had effective lengths similar to those experienced in building design (Korol and Sivakumaran, 2014) with simply supported ends. That research showed that the energy dissipation was typically 3.5 times that which would be obtained by multiplying the plastic moment by the angle formed at a plastic hinge. However, if single hinges only are assumed (as presumed by NIST (2008b)) the dissipative energy can therefore be conservatively estimated to be increased by the above factor for purposes of computing energy dissipation potential for those columns whose strength was unaffected by the fires at the time of collapse initiation.

5. Energy Absorption by Floor Slab Crushing

In addition to columns subjected to buckling and crushing, there was a great deal of pulverization of concrete involved in the collapse of all three WTC buildings. Several studies suggest that concrete, being a brittle material will pulverize in accordance with its specific fracture energy value, GF (Abdalla and Karihaloo, 2003). However, tensile stresses are the basis for experimentally determining this property, and when a hard body such as a collapsing girder impacts a floor slab below, the applied forces cause both localized crushing of the concrete floor's surface, and lateral displacements that would typically be resisted by a steel mesh or spandrel beams offering resistance to such movements. In other words, such events do not at all resemble fracture by wedge-splitting or point loading, which are methods used to calculate GF.

Indeed, the energy needed to pulverize a slab by crushing is substantially higher than one would compute using the models proposed by others (Bazant et al., 2008, Greening, 2006). However, researchers in the mining and milling industries have developed empirical relationships that link energy inputs to the type of equipment employed to break-up brittle materials into smaller sizes. For example, grinding and crushing methods are commonly used in those industries for which knowledge of energy inputs is of importance for procuring equipment needed for a given production process. A commonly used equation for determining the energy needed to break up rock-type materials such as by grinding was developed by Bond (1952), while for crushing, Eloranta (1997) amended the Bond equation given below to account for such a method that is much less efficient in pulverizing such materials.

The Bond formula itself is given as

$$E = 10W_i\left(1/\sqrt{x_f} - 1/\sqrt{x_i}\right), \tag{1}$$

in which E is the energy per unit mass to pulverize particle x_i to size x_f expressed in microns (μm), while W_i is the energy required to pulverize a given rock-type material from theoretically infinite size to 100 microns. The factor 10 in Eq. (1) is actually $\surd$ 100 μm, thus providing dimensional consistency. Traditionally, E and W_i were both established in units of kilowatt hours per ton (kWh/t), but for our tests, we chose units of J/kg, and as such, have to multiply the right hand side by 3600. Eloranta's modification for crush-type pulverization is simply to multiply the right hand side of Eq. (1) again, by a factor 3.4 which is a very significant amplification of energy needed for reducing brittle materials to smaller particle sizes.

For our research, we undertook penetration load tests on rectangular reduced scale models employing a solid 50 mm square sized steel loading block on both unreinforced (Korol and Sivakumaran, 2012) and shrinkage steel reinforced concrete slabs (Sivakumaran et al., 2014), light weight and normal strength, to better simulate the action of penetration-type loadings from falling debris that is associated with storey-to-storey collapses. To estimate the energy potentially available to be absorbed through a combination of crushing and general breakup of floor slab areas not experiencing a direct impact by a falling girder or beam expected to occur during a collapse event, we used a combination of Bond and Eloranta amended expressions for our slab specimens to compute a work index constant, W_i. Under the patch load of area a, applied to a slab having an overall size, A, it was assumed that Eloranta's 3.4 factor would apply, but for the remaining slab area, A-a, Eq. (1) would be more appropriate.

We therefore obtain a modification of Eq. (1) that retains W_i, given by:

$$E_c = \left\{10 * 3600\left(1/\sqrt{x_f} - 1/\sqrt{x_i}\right)(1 + 2.4a/A)\right\}W_i\,, \tag{2}$$

where E_c is the energy of combined methods of pulverization expressed in units of Joules/kg. For a/A values of 0.01, 0.04 and 0.16, we obtained values of W_i that averaged 4.0 kWh/t (Sivakumaran et al., 2014), a value that seems reasonable when compared with Doering International's values for blast furnace slag, ranging from 12 to 16, while cement clinker is noted as having a value of 15 kWh/t (Doering, 2011).

6. Floor Slabs to Particle Size Distributions

A major challenge in attempting to employ Eq. (2) is the question of what x_f value(s) to use. In the case of WTC 1 and 2, video recordings clearly showed that a vast amount of very fine dust was produced during their respective collapse events. And, the finer the particle sizes, the higher will be the energy inputs needed to create such dust, through what is known as comminution theory. However, our focus is on WTC 7, the floor areas being of normal weight concrete (2,400 kg/m3), nearly an acre in size, i.e. 3853 m2, denoted as A_f in what follows. Essentially the structure collapsed in its own footprint, so a distribution of particle sizes for the steel mesh reinforced floors has to be a guesstimate, and one which offers a lesser degree of very fine sizes than that which the twin towers experienced. One finding from our slab tests was that the weight of pieces having an average size > 20 mm was somewhat over 50% for the largest slabs tested (a/A < 0.16). Assuming for a typical collapsed floor that 50% would be large chunks, say 100 mm in size, with the remaining x_f bits retained equally in weight on sieves of sizes: 20, 5, 1.25 mm, and 630, 160, 60 and 30 μm, (the standard array in concrete lab test facilities) i.e. 7.1% for each of the seven, we obtain from Eq. (2) and with W_i = 4.0 kWh/t, a value for the energy dissipation potential for confined concrete, ED_c = 4900 J/kg. A detailed description of several scenarios conceived is noted as no.4 in Tables 3 and 4 of an earlier paper (Korol and Sivakumaran, 2014). We will employ the above ED_c value when we tally up the dissipative energy contributions.

7. Energy Considerations for Progressive Collapse

The analysis to be pursued avoids the controversy of the speed of descent of the structure during the collapse event itself. Our focus is only on the potential energy of the live and dead loads existing on the floors and roof above the level of the debris pile (estimated to be the 7th floor), and the built-in energy of the structure itself that is restricted to the columns and the concrete floor slabs. In this determination, we are ignoring any permanent plastic deformation of the girders, floor beams and connections that no doubt would also have played a role in resisting the collapse of the structure.

Firstly, we will consider the potential energy of the block of storeys above the two floors that are claimed to have been the most severely damaged by fire, i.e. levels 12 and 13. We know that WTC 7 remained motionless until late afternoon on that fateful day in September

2001, i.e. more than 6 hours after fires started in lower floors due to burning debris from the collapse of WTC 1. Since structures are designed to have safety factors to account for overload conditions, building codes prescribe load factors that apply to both dead and live loads. A reasonable estimate of safety for the conditions at the time prior to 5:20 pm is that the actual live load is considerably less than the factored design live load by at least a factor of 3. If L is denoted as the live load per unit area, 1.5 L is frequently used in the design of the structure. If D denotes the dead load, then 1.25 D is oftentimes employed in design. An additional factor to consider is the resistance factor which recognizes the possibility that the strength of structural members might be somewhat less than that specified, and as such the nominal resistance of a member or the full structure for our purposes can be given as $(1.5L + 1.25D)/ \Phi$, where $\Phi < 1$ is known as the resistance factor, varying from about 0.6 to 0.9 depending on the material. Since the structure was essentially vacant during its collapse, occupancy loading can be assumed to have been virtually zero, but those materials housed within office spaces and untouched by fire would remain as part of the mass contributing to L with the total being < 0.5 L. Meanwhile, dead loads D would generally be reduced only slightly due to combustion of some materials such as permanent partitions. A reasonable estimate, then, is to assume that in- service loads per floor in a fire scenario would be $M = 0.5\ L + D$. Accounting for the Φ factor, suggests that an overall factor of safety of 3 might be reasonable.

The consequence of a factor of 3, therefore suggests that one would require slightly more than the equivalent of two-thirds of the 82 columns (below floor 45) to have to totally fail while slightly fewer than 1/3 would be left resisting the loads above. At the instant that the building was about to collapse, therefore, we assume that 27 remained unscathed on each of floors 12 and 13 while the other 55 would have succumbed. Of course, such a scenario would be based on all columns having the same size and loading, which was not the case in reality. However, we make a not unreasonable assumption that if all the column sizes are known, an average size within the series of H-shapes that were employed in WTC 7's construction, could be selected that meets the same overall strength capacity on each floor as those that comprised the assemblage of columns existing at the time.

8. Potential Energy Portions

To be consistent with Bazant and Zhou's theory (2002) of crush-down followed by crush-up, we postulate three distinct contributions to gravitational potential energy at the time that the structure was poised to collapse. These we compute as follows:

- There exists an upper block of 35 floor levels (14th floor up to and including the roof) that will move downwards as a rigid block and which stops its motion at level 7 . It is represented as Block A in Fig. 1 with a height of 7 H_i above floor 7, where H_i is a single storey height = 3.89m (12'9"). Each floor, with the exception of those associated with storeys 21, 22 and 23, has a prescribed mass $M_i = \{(D + 0.5\ L)\ A_f\}/g = [3.6 + 0.5 (2.4)](3853)(1000)/9.81 = 1{,}885{,}000$ kg while the three noted above have values of D and L of 4.3 and 3.6 kPa respectively, thus raising the mass value on those floors to be 2,396,000 kg, which we denote as M_j. Note that the above mass values were obtained from Cantor information sheets (1985), and confirmed by NIST's draft for public comment report, chapter 2, "WTC 7 Building Description" (NIST 2008c). These mass totals and are presumed not to include the self-weight of the columns to be addressed below.
- Then, there is the group of floors that drop one upon the other in a series of collisions that involve impact energy losses as computed by the conservation of momentum principle. Each impact in turn, involves a slightly lesser amount of energy loss. For example, the first impact involves a drop in velocity that's dependent on the mass ratio of 35 levels melding into floor 13 to give a reduction in kinetic energy of 5.5%. However, for the case of five added floors impacting the 8th level, the ratio is dependent on the 40 floors above merging with the one below, with the result that the kinetic energy is reduced by 4.8%. On average then, we can assume a 5% drop in potential energy during such collisions for the Block B group of floors (8th to 13th inclusive). Such an assemblage, ending the crush-down phase of collapse, drops on average 3.5 H_i while the mass of colliding storeys is 6 M_i. Fig. 2(a) shows the final crush-down collapse state with all floors above storey 13 having toppled onto floor 7.
- Finally, there is the assemblage of floors above the 14th whose potential energy is related to the crush-up phase of collapse. Since there are no floor collisions during this collapse phase, we need only multiply the total mass of 35 levels with the centroidal height above the 14th floor (resting at level 7) taken as 17 H_j, a value slightly below the mid-height value of 17.5 H_j. The Cantor drawings indicate a range of storey heights of 3.89m (12.75') to 4.52m (14.83'), with the average value of H_j = 4.4 m (14.4'). An additional mass to consider is that due to the totality of column self-weights for Block A (Fig. 1(a)), m_{Acol}. From the column schedule for WTC 7, the total mass tallies up to a total of 6,530,000 kg, a value that is 9.7% of the value calculated as $\Sigma\ (0.5\ L + D)$ for the 35 levels.

9. Total Gravitational Potential Energy

a) Crush-down

At the start of crush-down, Block A will drop H_i , collides with floor 13, which then adds floor mass level with some slowdown in velocity, and continues its motion down to our presumed debris pile level at floor 7. The total potential energy for Block A to move downward from level 14 to level 7 is: $[(32\ M_i + 3\ M_j) + m_{Acol}]\ g \cdot 7\ H_i = 19.78 \times 10^9$ Joules. For convenience, we denote the term in square brackets as M_A which computes as 74,038,000 kg.

In addition, storeys 13 to 8, noted as Block B in Fig. 1(a) could potentially displace downwards to level 7 and which would involve collisions when impacts occur. Those assoiciated floors will also contribute to crush-down potential energy. As noted they drop on average an amount of 3.5 H_i , and when accounting for losses of about 5% due to impacts of Block A with floors 13, 12, 11, 10, 9 and 8, the result is a contribution of [6 M_i + m_{Bcol}] g · 3.5 H_i (1- 0.05), where m_{Bcol} for those 6 storeys = 836,600 kg. Again for convenience we will refer to the Block B masses as $M_B = 6M_i + m_{Bcol}$, equal to 12,147,000 kg, with its potential energy computed to be 1.541 x 10^9 Joules.

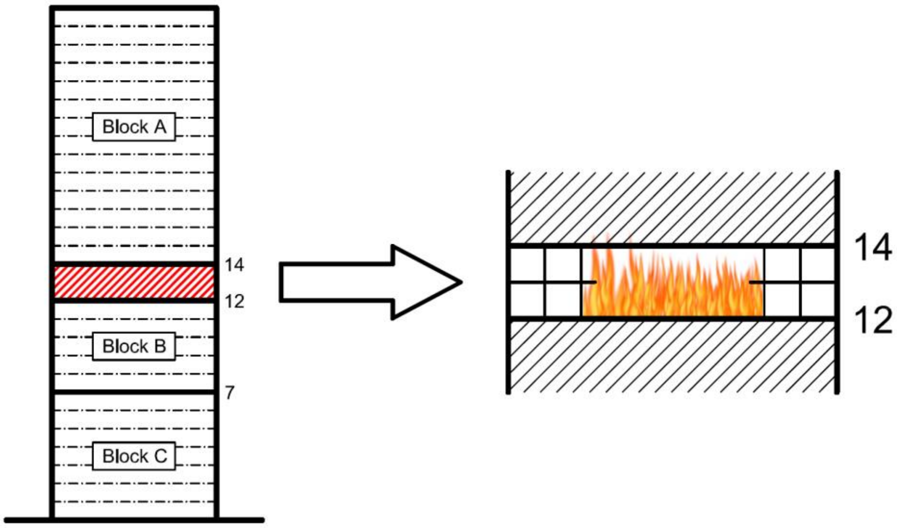

Fig. 1. Structure poised to collapse.

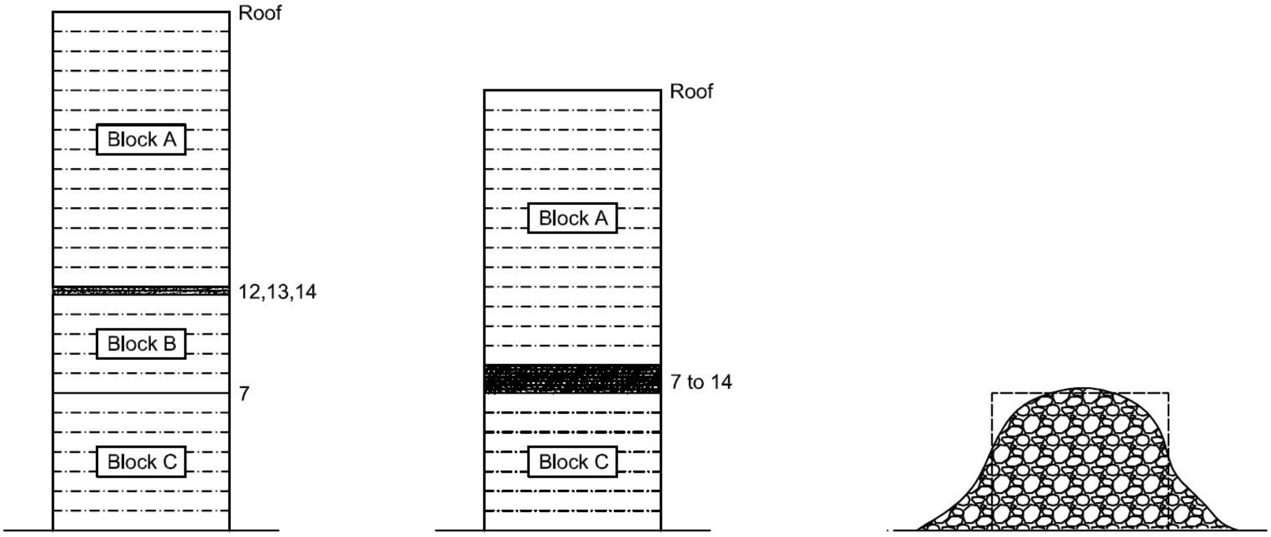

Fig. 2. Theoretically possible collapse states: a) Crush-down to Floor 12; b) End of crush-down phase; c) Debris pile idealized.

b) Crush-up

As noted in subsection (3), this potential energy contribution is simply the product of floor masses comprising Block A with the gravitational constant and the centroidal distance above the debris pile. As noted earlier, the total mass including the column self weights is given as M_A, while its centroidal distance is approximately 17 H_j. The product that includes the gravitational constant g = 9.81 m/sec^2, results in a loss of potential energy of 54.3 x 10^9 Joules.

Summing up all the potential energy contributions results in a value of 75.7 x 10^9 Joules. The question to be answered, then is: How does this value compare with the total potential dissipative energy that's available from the compressed H-shaped WF columns and concrete floors possessing shrinkage steel mesh? We will address this issue in the next section.

10. Energy Dissipation Considerations

a) Crush-down

We begin our analysis considering only the absorptive energy capacity of the structure during the crush-down phase of collapse. Due to the large number of columns existing at any floor level and the variety of sizes within the W360 section class, we identified an average size that suits resistance under axial compression for individual storeys. Information pertinent for the lower storeys subjected to crush-down is provided in Table 1.

Considering all the columns in the storeys noted as having the same cross sectional properties (due to the rolled shape size limitations), we obtain for the total of 464 columns with plastic section modulus values, Z_y (col. 5) (noted in column 5 of Table 1) = 10,700 x 10^3 mm^3, a plastic hinge rotation of 0.9 π , together with an average

yield stress of F_y = 276 MPa, we obtain a total column energy dissipation value of Σ [(464 x 0.9 π x 10,700 x 10^3 x 276)(3.5)], where the 3.5 factor was determined from tests performed at our structural laboratory at McMaster University (Korol and Sivakumaran 2014). The total then computes as 13.56 x 10^9 Joules.

Table 1. Average core and perimeter column values (Block B).

Storeys in Crush-Down Collapse	No. of Columns Resisting Load	Avg. Weight in kN/m (lbs/ft)	Column Size to Suit	Plastic Section Modulus Z_y 10^3 mm^3 (in^3)
13	27	8.15 (562)	W360x900 (14W605)	10,700 (652)
12	27	8.44 (581)	“	“
11	82	“	“	“
9-10	82	8.57 (590)	“	“
7-8	82	8.60 (592)	“	“

Considering all the columns in the storeys noted as having the same cross sectional properties (due to the rolled shape size limitations), we obtain for the total of 464 columns with plastic section modulus values, Z_y (col. 5) (noted in column 5 of Table 1) = 10,700 x 10^3 mm^3, a plastic hinge rotation of 0.9 π, together with an average yield stress of F_y = 276 MPa, we obtain a total column energy dissipation value of Σ [(464 x 0.9 π x 10,700 x 10^3 x 276)(3.5)], where the 3.5 factor was determined from tests performed at our structural laboratory at McMaster University (Korol and Sivakumaran 2014). The total then computes as 13.56 x 10^9 Joules.

Regarding concrete pulverization, we'll assume that fires were so hot on floors 12 and 13 that the concrete would have been weakened sufficiently from the heat that their ability to absorb energy would have been fully compromised. Including then, only floors 7 to 11 inclusive, and assuming normal concrete with an average thickness of 101.6 mm (4”) we get for the 5 floors a total amount of energy equal to 32.01 x 10^9 Joules. The total amount of energy dissipation during crush-down therefore is the sum of the two which is 45.57 x 10^9 Joules.

b) Crush-up

For those storeys above the 14th floor, we only need to undertake a rough calculation about equivalent column sizes, since our computations indicate that 60% of the total potential energy has already been accounted for, and there are 35 levels (34 storeys) that will involve both plastic hinge buckling of columns and pulverization of concrete slabs. It is clear with only rough computations that the energy dissipation far exceeds that of the gravitational potential energy of the building collapsing into a debris pile at floor level 7. As such, we assume that storey 31 (half way up Block A) is representative for that assemblage of columns.

An average size *W* section at storey 31 (Cantor 1985) results in selecting a W360x551 possessing a plastic section modulus of 6,050x10^3 mm^3 about the weak axis of bending. For the 2752 columns (82 and 70 respectively for storeys 14-44 and 45- 47) in Block A, the total amount of column energy potential works out to be 45.5 x 10^9 Joules. Meanwhile, the crushing of 34 floor slabs in Block A computes as an energy dissipation of 218 x 10^9 Joules, resulting in a total of 263.5 x 10^9 Joules for this upper block of storeys.

Then, when we add in the value for Block B's crush-down total of 45.6 x 10^9 we get a grand total amount of energy dissipation of 309.1 x 10^9 Joules. This value, therefore, is 309.1/75.7 or 4 times the gravitational potential energy associated with a full collapse of the structure. However, it's of interest to carry this analysis one step further.

11. Where Does the Motion Stop?

We begin with the energy balance equation for computing the velocity of Block A after a one storey drop to floor level 13. The only energy dissipation will involve the 27 columns that were almost sufficient to support the loading above. Since the initial energy state has zero velocity the following equation applies:

$$ {}^{1}\!/_{2}\,(M_A)\left(v_A^f\right)^2 = M_A g H_i - 27 * 0.9\pi Z_y F_y * \alpha_{hfac}, \qquad (3)$$

in which v_A^f is the velocity of Block A at impact with floor 13 and α_{hfac} is the plastic hinge correction factor that accounts for axial compression taken to be 3.5 as noted earlier from our McMaster tests. As Table 1 indicates, the equivalent column size needed to offer the same or slightly higher resistance than the actual average size is a W360x900. Substituting appropriate values into Eq, (3) in which M_A = 74.0 x 106 kg and H_i = 3.89 m results in a value of v_A^f of 7.42 m/sec.

The next stage involves conservation of linear momentum that accounts for a reduced velocity during motion Block A plus one floor in storey 12. The initial storey velocity of the moving front is therefore 35/36 times 7.42 to give the initial velocity of v_{A+1}^i of 7.21 m/sec. (Note that the subscript “*A+1*” denotes Block A plus an added storey). Our equation for the 12th storey must include both potential and kinetic energy inputs to evaluate to determine that storey's final velocity. And so, in this case, we have:

$$
{}^1\!/_2\,(M_{A+1})\left(v_{A+1}^{f}\right)^2 = {}^1\!/_2\,(M_{A+1})(7.21)^2 + M_{A+1}gH_i - 27 * 0.9\pi Z_y F_y * \alpha_{hfac}\,. \qquad (4)
$$

Solving for the 12th storey final velocity gives a value of $v_{A+1}^{f} =$ 10.37 m/sec

Moving now to the 11th storey, conservation of momentum gives v_{A+2}^{i} a value of (37/38) times 10.37 = 10.097 m/sec. In this case we have 82 columns offering resistance and a concrete floor area, A_f, that is subject to pulverization. The equation that applies in this case is:

$$
{}^1\!/_2\,(M_{A+2})\left(v_{A+2}^{f}\right)^2 = {}^1\!/_2\,(M_{A+2})(10.097)^2 + M_{A+2}gH_i - \left[82 * 0.9\pi Z_y F_y * 3.5 + ED_c A_f d_c \rho_c\right], \qquad (5)
$$

where ED_c is the pulverization value or 4900 J/kg, d_c is the slab depth of 101.4 mm (4"), and ρ_c is the concrete density of 2400 kg/m^3. The floor area A_f = 3853 m^2 as noted earlier.

Substituting the appropriate values results in the right hand side ends up as a negative value. The conclusion, therefore, is that the structure's collapse is arrested in the 11th storey. Indeed, it is the pulverization component that is responsible, being about twice the energy dissipater compared to the steel columns. This result would mean that Block A, with two floors added, is stopped when impacting the 11th storey floor. The structure then is restricted to collapsing to 3 storeys.

12. Conclusions

Our objective at the beginning of the study was to simply investigate whether there was enough energy dissipative capacity in the 47 storey WTC 7 high rise steel frame structure to offset its gravitational potential energy for the case of an extreme fire loading event. As noted by NIST in their NCSTAR 1-9 report, very hot fires are claimed to have been present in the 12th and 13th floors for several hours during the late morning and afternoon of 9/11 sufficient in fact to cause the total collapse of the building. The authors decided to revisit the problem to ascertain for ourselves whether the structure's demise could have happened under conditions of two storeys being substantially weakened by the heat.

Regarding our focus on gravitational potential energy versus the dissipative energy possessed by the structure, we found that the former was insufficient to cause a total collapse scenario to occur by a factor of 4. The question then morphed into a more detailed analysis whereby we wanted to know the extent of a partial collapse. Indeed, our assumptions and analysis based on Newtonian mechanics clearly show that a very limited partial collapse would have been possible but that it would have been restricted to the storeys in which the fires occurred and to the one below. Some might argue that an upper storey would have been more vulnerable, however, the column sizes involved were so little different, we decided to adopt the Bazant hypothesis that crush-down would take precedence over crush-up. As noted, our progressive collapse investigation involved a storey-by-storey analysis that was initiated with Block A, the base of which was presumed to be the 14th floor. It was presumed that a crush-down descent would begin with the equivalent of only 27 columns capable of resisting the column and service loadings that the design engineering firm, Irwin Castor, prescribed in their loading schedule for dead and live loads. This number was based on the design possessing an overall factor of safety of 3, a not unreasonable factor that is consistent with building code standards in general. As well, we treated perimeter and core columns as being equally loaded across floor areas that were vulnerable, since WTC 7 is known to have come straight down as observed by video cameras.

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