On the Collapse of the World Trade Center in New York on Sept.11,2001

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Abstract: The generally-accepted explanation of the collapse of the World Trade Center towers on September 11, 2001 is based on the speculative "theory" of progressive buckling of bearing columns at the speed of free fall triggered by creep buckling of the columns of the floor subject to the conflagration from the spilled fuel, and by dynamic impact of the upper structure. In the present paper it is shown that this official "theory" is wrong because it is built on false assumptions and incorrect calculations. The "theory" cannot explain the free fall, explosion sound, and pulverization of the buildings as well as other facts of this event. The simultaneous collapse of the neighboring 47-story tower directly contradicts to the "theory". It is shown that, consistent with all known facts of the matter, the scenario of all collapses was this: (i) heating of bearing columns in the "hot" spot caused high compressive thermal stresses in these columns, (ii) these stresses combined with internal stresses triggered a fracture wave, and (iii) the fracture wave disintegrated the entire building by invisible cracks for less than 0.1 s producing the sound of explosion and providing the conditions necessary for free fall of steel fragments and dust clouds of tiny fragments of glass, marble and concrete. The theory of fracture waves, see Appendix 1, supports this scenario. The official " theory" is placed in Appendix 2.

Keywords: World Trade Center, tower, building, column, collapse, explosion, structure free fall, debris, structure pulverization, fracture wave, thermal stresses, internal stresses, creep, buckling, dynamic impact, progressive failure, triggering mechanism, accurate vs. approximate analysis.

Contents

1. Introduction

"Why did you think the towers collapse?", Larry asked his guest, a prominent member of the September 11 Commission, on a recent Larry King show. "This is still under investigation", the guest answered. Evidently, the public has not, as yet, accepted the "theory" by Bazant and Zhou (2002), see Appendix 2.

> Meanwhile, the engineering community has, without any hesitation, recognized the “theory” as correct and comprehensive. This author has felt this official recognition on his own skin after the editors and anonymous referees of numerous technical journals refused to publish his understanding of the collapses as contradicting to this “theory”. The most important conclusion Bazant and Zhou derived from their analysis was that the WTC collapse was an unavoidable consequence of the terror act. This conclusion was necessary to both sides. To the American government, for to make the turn to the new policy designed before. To terrorists, as a recognition of success of their strategy and an encouragement to start jihad around the world. Meanwhile, on the opinion of the same engineering community, this terror act could not cause a WTC collapse. Otherwise, all people would have been evacuated from the buildings during the fire, and 300 firemen would not have been ordered to climb up, so that, instead of three thousand, the fatalities would not have exceeded about one hundred people. The collapses happened unexpectedly. My point proved below is that Bazant&Zhou’s analysis and conclusion are wrong and that the collapse was a result of insufficient knowledge of fracture, and especially fracture wave, mechanics ignored both in the construction of towers and in the prediction of what could happen after the terror act.

The “theory” has suggested the following scenario of the collapse: creep buckling of bearing columns of the critical floor, free fall and dynamic impact of the upper structure, and progressive, floor-by-floor, buckling failure of bearing columns of the underlying structure. This “theory” has been unable to explain these well-known facts of the matter:

(i) Free fall regime of all collapses;

(ii) Sound of explosion produced by each collapse;
(Sound is generated by cracking. If the cracking had continued for ten seconds, as the “theory” asserts, a boom would have been heard, not an explosion.)

(iii) Pulverization of the buildings collapsed .
(By the “theory” the debris after the collapse would have consisted of steel segments of columns about two meters long, and nothing more.)

According to the “theory” the neighboring 47-story building should NOT have collapsed. But, it did.

According to the “theory” the Empire State Building should have collapsed in 1945 under similar conditions of aircraft crash and conflagration. But, it did NOT.

Meanwhile, for every person familiar with industrial implosions, when a building is intentionally demolished by uniformly distributed explosives to produce small debris for their easier transport, the WTC collapse has strikingly resembled that of a designed implosion caused by previously distributed explosives. Indeed, each tower collapse took about ten seconds, that is all parts of each building were falling free, without any resistance. It is exactly what happens after a building is disintegrated by explosives. It is no wonder that the conspiracy theory, consistent with the well-known facts of the matter contrary to the official “theory”, has become widely spread in the world. In the speech on the popular TV channel C-SPAN on April 18 and May 7,2005 David Ray Griffin who is a famous public figure in the U.S. gave an explicit overview of the events of September 11, 2001. He indicated the following facts: (i) Close ties of the families of Bush and bin Laden in common oil business in Saudi Arabia; (ii) bin Laden was a CIA agent in the 1980s when he fought against Russians in Afghanistan; (iii) No one from the bin Laden family (brothers, sisters, wives, adult children) has ever been detained or prosecuted; (iv) Many members of the bin Laden family living in the U.S. before September 11,2001 and celebrating these events were, without any investigation, allowed to leave the U.S. using an airplane that flew over the U.S. territory on September 12, 2001 when all other flights were strictly prohibited; (v) Several of 19 terrorists who committed the suicide mission on September 11, 2001 were arrested the day before because of invalid documents but, then, miraculously released; (vi) FBI and CIA knew about a terror act before that day; (vii) In December 2001 when bin Laden was in Tora Bora—which was well-known to the U.S. intelligence—the U.S.military refused from assaulting the bin Laden troops and allowed him to escape; (viii) Investigation of the collapse of the WTC towers was assigned to the National Institute of Standards (NIST), that is a government institution, and not to much more prestigious bodies like MIT or Harvard which are private and more independent institutions (indeed, to the best of my knowledge, in NIST there are no experts in fracture mechanics, at all) ; (ix) The U.S. raised Al Caeda and many its branches including the Chechen body. The terrorist organizations have been affiliated with CIA and other U.S. intelligence agencies that selected, financed, instructed, and directed the terrorists. Many facts of this affiliation can also be found in the book "The War on Truth" by Nafeez Ahmed. The discussion of this book took place on the American TV channel C-SPAN2 on July 23 and 31, 2005. Recently, I myself had an encounter with some Chechens from Russia who admired bin Laden, lived for free on government subsidies, took the instruction here, and were, better than a common American, protected by the American government. And so on.

David Ray Griffin rejects the official theory of the WTC collapse as a hastily concocted one contradicting to the well-known facts of the matter. Indeed, the paper of Bazant and Zhou where the official theory was first published was submitted on September 13, 2001. I, personally, can't imagine that such an important study could be done for one day. Dr. Bazant who is a renowned scientist well-known by his work in creep and fracture of concrete was, probably, used to mislead and misdirect the engineering community. Despite the evident blunders and miscalculations indicated in Sections that follow his theory has never been criticized in scientific press. Moreover, Dr. Sunder from NIST using a numerous research team and unlimited resources invented a numerical model supporting all basic points of the theory. All facts of the collapse indicated above as well as the fire itself were, again, ignored in this model that describes the collapses seen on the pictures obtained from cameras outside the building. Surely, the cameras could not notice the cracking of the building just before the collapse.

On the opinion of David Ray Griffin, U.S. government agents acting together with bin Laden used the terrorists for their mission , mined beforehand two towers and the neighboring 47- story skyscraper by explosives which were detonated in a while after the crashes. David Ray Griffin thinks the September 11 events like the arson of Reichstag in Germany in 1933 were necessary for those government circles who designed the plan of the American rule of the globe in the document entitled "American

Century" issued still in 1993. Wolfowitz who is the first deputy of the Secretary of Defense has been the mastermind of this plan. He is viewed as the main brain power behind the wars in Afghanistan and Iraq. Indeed, September 11,2001 became a landmark separating the American history before and after. A myth that some peoples hate Americans and wish to kill them was created. All international laws and treaties were broken, and the era of preemptive wars, interventions and occupations has begun. The American military, police, and intelligence have gotten the right to search and detain anyone on the Earth without an indictment and to use any means including free access to finances, mail, telephone talks, private life, etc up to the assassination. I, myself, was twice stopped—probably, because of my beard—and my car was searched for explosives and weaponry. Miami metropolitan area is under regular surveillance by police, guards, and dogs seeking for smell of explosives. The recent attempt of assassination of Chavez who is the President of Venezuela is another example. The wars in Afghanistan and Iraq, the first step for the control of the Arabian and Caspian oil according to the "American Century", started just after September 11 and are still on. However, the military expenses for a much bigger war are many times greater than for anti-terror activities and greater than the military expenses of the rest of the world. Enormous funds have been released for strategic arms including super-penetrating bombs, interception stations, a new generation of submarines and nuclear bombs, the armament of military satellites, and on, and on. The new arms race has begun at an unprecedented rate. Starting the Iraq war, President Bush warned that the use of the "nuclear weapon is not taken from the table". No doubt, it would be used to eliminate Baghdad if the American troops were defeated; and so, the guerilla war was the only choice for Iraqi patriots. Who, specifically, would be interested in a war or, moreover, a big war? The answer is evident, "Nobody" and "There are no enemies, at all". However, there are about four hundred billionaires and about four million millionaires in the United States. They carry out the main mission of the U.S. which is "Money is the power". Their power is tremendous , although hidden due to competition like the energy of nucleons in a nucleus. It is multiplied many times by the sixty-million army of smaller investors supported by media, military, and 14 intelligence agencies. One American billionaire can make his government in, and control, such country as Estonia, or Armenia, or Georgia. He does not do this action only because he does not see how to increase his wealth by this way-- it is not a good investment for him , so far. The American passion for making money embodied in corporations creates the enormous resultant force no state, country, or government can withstand. Nobody can surpass them in money-making business based on legitimized deception and enforcement. Like a good sailor who can drive a sail boat against a wind this force can drive this great country against the wind of morality, public opinion, fear of nuclear war etc in any direction where is the smell of money. After the fall of Soviet Union, when the anti-money world system collapsed, dollar via convertible currencies became the master of the whole world. The U.S. is run not by the President or Congress, but by the Federal Reserve which is a private organization of billionaires.

In what follows, it is shown that the official "theory" of the WTC collapse is built on false assumptions and miscalculations, and hence IS wrong; and a scientific explanation consistent with all known facts is suggested.

2. Triggering mechanism: thermal stresses vs. creep

"A loss of protective thermal insulation of steel columns during the initial blast accelerated the heating of the columns to very high sustained temperature well above 800°C which lowered the yield strength and caused creep buckling of more than half of the columns in the critical floor, so that the upper part of the structure above this floor fell down and, by enormous vertical dynamic load, destroyed the underlying segment of the tower; and so the series of impacts and failures proceeded all the way down", the official "theory" says, when paying no attention to thermal stresses and residual technological stresses arisen from rolling, welding, assembling, etc. Amazingly, the "theory" ignores even the main event – the combustion of spilled fuel in the critical floor, the event that caused all the collapses.

All assumptions and claims of this "theory" are false. First, the loss of the protective thermal insulation of more than half of the 260 columns of the critical floor by the initial blast is nothing but a miracle necessary for the "theory" because for creep time is essence. Remember that the time between each crash and collapse took about one hour which was, by itself, a very little time for a creep action in a steel column at the level of stresses, at least, three times less than the yield strength and/or the buckling stress at normal temperature, due to the safety factor, even if the entire lateral surface of the column was exposed to the temperature 800°C all this time.

The rate of heat propagation is controlled by the thermal diffusivity, which is equal to 12×10^{-6} m^2/s for steel and about a fifty times less for the protective thermal insulation. How fast is this process in terms of time? Let us provide an accurate example. Suppose the initial temperature of a steel half-space is zero. It takes one hour to increase the temperature to 650°C at the distance 8 cm from the surface kept at 800°C all this time. For the thermal insulation, the corresponding distance is about 1 cm, all other conditions being the same. In other words, one hour is about the time necessary for the heat to penetrate through the protective thermal insulation of a bearing column; it takes one more hour to warm up the column itself. There is no time for creep action.

Secondly, the assumption that 800°C was the temperature of four-meter-long bearing columns of the critical floor during the fire, is quite frivolous. Again, let us examine an example of accurate calculation. Suppose n-octane fuel is burned in the constant pressure, adiabatic combustor of an aircraft engine with 40% excess air, and the fuel is injected into the combustor at 25°C while the air from the compressor enters this combustor at 600 KPa, 300°C. One can find that the combustion products leave the combustor for the turbine at the temperature 769°C, so that the mean temperature of turbine blades is well below 700°C. These are the real conditions of the fuel combustion in the engines of the Boeings that crashed into the towers.

Let us compare the combustion of the fuel spilled in the critical floor of the WTC tower with the combustion of this fuel in the Boeing engine. The combustor will be the whole floor, open-to-air, space with a liquid fuel layer on the bottom, with the air entering this combustor from the atmosphere at 100 KPa, 25°C. Compare the temperature of the Boeing turbine blades with that of thermally-protected columns of the floor. The combustion in the engine runs under the perfect conditions of homogeneous turbulence in a homogeneous mixture designed to achieve the temperature of combustion products as high as possible. The combustion in the open, non-adiabatic floor is, evidently, incomplete, far from the stoichiometric balance, with cold air and a low air-fuel ratio, with the reaction taking place in convective flames providing a very non-uniform distribution of temperature in space and time. For example, the temperature of the tip of the convective flame of a candle can achieve 500°C but you can put it out with a finger because the mean temperature of the flame is below 100°C. And so, the mean temperature in the burning surroundings of the bearing columns was probably below 500°C while locally, at some spots close to the ceiling of the floor, it could achieve 1000°C and higher because of high adiabatic flame temperatures of the fuel. For creep buckling to be true, the entire column should be at a high temperature for a long time.

Thirdly, the decrease of the yield strength of steel was too little to play any role in the collapses. Structural hot-rolled steel used in columns has the yield strength about 600 MPa and the ultimate strength about 900 MPa, at 20°C. At 800°C the numbers are 10 to 20% lower while the nominal stress in columns was, at least, three times less than the yield strength.

From this analysis of conflagration, it follows that the claim of creep buckling of the "theory" is groundless. A measurable creep of structural austenitic steels starts from about 540°C. Meanwhile, this and higher temperatures could be achieved only locally, in the top parts of some bearing columns where the flame temperature was maximal. And because of the thermal protection, these temperatures could be sustained during some time much less than one hour.

For the "theory", it is essential that each bearing column of the floor should be, from the bottom to the top, heated to one and same high temperature sustained for a long time, because in the case of uniform heating of all columns there are no thermal stresses in the columns, so that the thermal stresses can be ignored. If only some of the columns are heated, the thermal stresses arise that can achieve an order of αET where α is the thermal expansion coefficient, E is Young's modulus, and T is the temperature. For steel $\alpha = 12 \times 10^{-6}$ /°C and $E = 200$ GPa so that at 800°C the thermal stress can be as high as 2 GPa which is about four times greater than the yield strength of steel at 800°C, i.e. it is certainly unpracticable.

The calculation of the time-space distribution of temperature and thermal stresses in a building under the real conditions of a fire is a delicate procedure responsible for providing a correct prediction or explanation of a final outcome. Whether a building would collapse or be preserved depends on the thermal stress distribution. Any material volume or structure will be torn into pieces by thermal stresses if some part of the structure is heated too fast to a high temperature. A numerical model of the collapse should include, as the most important part, the vaporization of liquid fuel layer , the gas dynamics of reacting mixture in the critical floor, heat exchange, and the development of temperature and thermal stresses in the building. Such a model has not , as yet , been done.

Just for the purpose of rough estimate, let us do some calculations using the notion of a "hot spot" inside the building. The bearing columns in the hot spot are heated to one and same temperature T while the bearing columns outside the hot spot retain the initial temperature $T = 0$. And so, the thermal stresses in the hot columns are compressive while in the cold columns they are tensile. In the case of the conflagration in the WTC towers and adjacent 47-story building, the core columns were probably in the hot spot while, at least, some bearing columns of framed tube cooled by atmospheric air were outside the hot spot. Compressive thermal stresses, being diffused only by bending floor trusses and cold columns of framed tube, penetrated far into cold columns of the underlying structure. Combined with gravitational and residual technological stresses, the compressive thermal stresses inside the building created a heating bomb like that of a Batavian tear, so that a fracture wave was born that disintegrated the entire tower for less than 0.1 s.

Let us remind that a Batavian tear, just taken from a glass bath and treated by fluoric acid to dissolve the cracked surface layer, has a core under high compressive stresses and a flawless surface layer under high tensile stress about 5 GPa. Breaking the tiny tail on the Batavian tear releases the elastic energy of compressive stresses in a fracture wave that propagates at the speed of sound and pulverizes glass into micron-size fragments. (See Appendix) Also, as a reminder the compressive residual stress from rolling in steel columns can achieve a half or more of the yield strength. Let us consider, in some detail, what happened during the conflagration in the critical floor.The vapor of liquid fuel spilled on the bottom of the floor got mixed with atmospheric oxygen of the floor and an occasional inflammation excited the exothermal reaction of the mixture so that, based on the above calculation of combustion, the temperature and pressure of combustion products in the floor could achieve up to 750 degrees Celsius and 400Kpa. This blast stage took some seconds. The gas pressure could not tear off even the cloth of someone inside the blast, not to say about the thermal protection insulation of steel columns. But, the pressure broke all windows and made the floor open to atmosphere. The comparatively steady stage of fire took about one hour. On this stage, cold air from outside supplying oxygen necessary for combustion flew in along the bottom of the floor while hot products of combustion flew out along the ceiling of the floor. The pressure of gas in the floor on this stage was about 100Kpa as outside. The combustion took place in convective flames, the bottom of which had the vaporization temperature of fuel, i.e. less than 100 degrees Celsius, while mean temperature on the top of flames, at the ceiling, could certainly achieve 800 degrees Celsius and higher due to high adiabatic flame temperature of octane. A linear approximation leads to about one meter long column top part under temperature 550 degrees Celsius and higher. It is the long horizontal trusses in the ceiling of the critical floor that could first experience the temperature increase and buckling from thermal stresses. Creep and softening of concrete in this ceiling , together with the buckling of the trusses, significantly decreased the support of the upper ends of the hot bearing columns in the critical floor during the fire. To demonstrate the action of thermal stresses within the framework of the “hot spot” model we assume in what follows that the bottom of the critical floor and the cold ceiling of the next upper floor are rigid while the ceiling of the critical floor is softening during the fire. Let us assume also that all hot columns are elastic up to buckling and all cold columns are elastic up to tensile failure.

Suppose S_A is the cross-section area of all bearing columns of the critical floor. Let us assume that βS_A is the cross-section area of the hot bearing columns heated to the temperature T and $(1-\beta)S_A$ is the cross-section area of cold bearing columns at the temperature $T=0$. As a result, the hot columns will be subject to the compressive thermal stress

$$\sigma = -\delta(1-\beta)\alpha ET \quad \text{where} \quad 0 < \beta < 1, \; \tfrac{1}{2} < \delta < 1, \tag{1}$$

while the cold columns will be subject to the tensile thermal stress

$$\sigma = \delta\beta\alpha ET \quad \text{where} \quad 0 < \beta < 1, \; \tfrac{1}{2} < \delta < 1. \tag{2}$$

The coefficient δ takes into account the elastic reaction of the upper ends of columns. For rigid floor trusses $\delta = 1$, and for very soft floor trusses, when the elastic reaction of supports is created by the columns themselves, $\delta = 0.5$. And so, the hot columns will be under action of the sum of compressive gravitational and thermal stresses while the cold columns will be unloaded by the thermal stresses. In this illustrative estimate, we ignore residual stresses.

A collapse can start either from tensile failure of cold columns or from the buckling of hot columns in the critical floor. Let us estimate the critical size of the hot spot for both cases.

Suppose that the buckling of hot columns occurs at $\beta = \beta_b$ and that - $f\sigma_Y$ is the nominal stress in all columns of the floor from the weight of the upper structure, where f is the safety factor and σ_Y is the yield strength of steel. Let $-f_o\sigma_Y$ be the stress in hot columns when the buckling occurs, where $f_o \geq f$ evidently. From here and equation (1) it follows that

$$f\sigma_Y + \delta(1-\beta_b)\alpha ET = f_o\sigma_Y, \tag{3}$$

and

$$\beta_b = 1 - \frac{(f_o - f)\sigma_Y}{\delta\alpha ET}. \tag{4}$$

Now, suppose that the failure of cold columns from tensile stresses occurs at $\beta = \beta_T$. From here and equation (2), it follows that

$$\delta\beta_T\alpha ET - f\sigma_Y = \sigma_b, \tag{5}$$

and

$$\beta_T = \frac{\sigma_b + f\sigma_Y}{\delta\alpha ET}, \tag{6}$$

where σ_b is the ultimate tensile strength of structural steel. Make the ratio β_b / β_T from equations (4) and (6)

$$\frac{\beta_b}{\beta_T} = \frac{\delta\alpha ET - f_o\sigma_Y + f\sigma_Y}{\sigma_b + f\sigma_Y}. \tag{7}$$

From equation (7) it follows that

$$\frac{\beta_b}{\beta_T} > 1 \qquad \text{because} \qquad \delta\alpha ET > \sigma_b + f_o\sigma_Y . \qquad (8)$$

For example, for typical values when $\alpha ET = 2\,\text{GPa}$, $\sigma_Y = 0.5\,\text{GPa}$, $\sigma_b = 0.7\,\text{GPa}$, $f_o = 0.5$, $f = 0.25$, and $\delta = 0.75$, we get $\beta_b / \beta_T = 5/3$.

It means that the collapse started from tensile failure of cold columns because the critical size of the hot spot in this scenario was less than that in the scenario of the buckling of hot columns. The hot spot was evidently expanding during the fire.

And so, the failing cold columns of the critical floor played the role of a tiny tail of a Batavian tear that explodes into small fragments when the tail is broken. The failure of the cold columns of the critical floor started the process of release of elastic energy of compressive stresses that occurred in a fracture wave because it is only the fracture wave that can pulverize material.

3. Dynamics: accurate vs. approximate analysis

According to the “theory” the upper part of the tower above the critical floor freely fell down in the beginning of the collapse and created an “enormous” dynamic stress in the bearing columns of the underlying structure, so that the maximum dynamic stress was 64.5 times greater that the nominal static stress in these columns from the weight of the upper structure. “This estimate is calculated from the elastic wave equation”, the “theory” says.

Let us verify this calculation. Suppose mass m falls down under gravitational force and hits the end of a vertical elastic column or bar at the speed V_o and sticks to the end. It is easy to find the material velocity v_x and stress σ_x in the column/bar arising from this impact:

$$v_x = \frac{mg}{SE}c + \left(V_o - \frac{mg}{SE}c\right)\exp\left[\frac{SE}{mc^2}(x - ct)\right], \qquad (9)$$

$$\sigma_x = -\frac{mg}{S} + \left(-\frac{V_o}{c}E + \frac{mg}{S}\right)\exp\left[\frac{SE}{mc^2}(x - ct)\right]. \qquad (10)$$

Here: $0 < x < ct$; t is the time from the moment of impact $t = 0$; x is the coordinate along the bar located at $x > 0$; E is Young’s modulus and c is the speed of elastic waves in the column equal to $\sqrt{E/\rho}$ where ρ is the density; and S is the column cross-section area. For $x > ct > 0$ both σ_x and v_x equal zero.

In particular, at the end of the column at $x = 0$ $t > 0$, the stress and velocity are:

$$\sigma_x = -\frac{mg}{S} + \left(-\frac{V_o}{c}E + \frac{mg}{S}\right)\exp\left[-\frac{SE}{mc}t\right], \qquad (11)$$

$$v_x = \frac{mg}{SE}c + \left(V_o - \frac{mg}{SE}c\right)\exp\left[-\frac{SE}{mc}t\right]. \qquad (12)$$

The maximum stress is equal to:

$$\sigma_x = -\frac{V_o}{c}E \quad \text{when} \quad x = 0 \quad t = 0. \qquad (13)$$

If the assumption of the "theory" about free fell of the upper structure is accepted, then $V_o = \sqrt{2gh} = 8.5$ m/s because the height of the floor $h = 3.7$ m and $g = 9.8$ m/s^2. For steel columns, $c = 5.1$ Km/s and $E = 200$ GPa, so that according to equation (13) the maximum stress in the columns of the underlying structure is equal to 340 MPa. Based on the indicated estimate of the "theory" the nominal static stress in these columns, that is mg/S, should be equal to 340/64.5=5 MPa which is a hundred times less than the yield strength of steel. It is unbelievable! Even a teen girl can produce such a pressure on the floor by her high heels. The approximate estimate of the "theory" is very inaccurate.

However, even the maximum stress 340 MPa from the impact, greatly exaggerated due to the free fall assumption, is about six times less than the maximum thermal stress 2 GPa. And so, the role of dynamic overload from the impact of the upper structure turns out to be secondary as compared to the thermal stresses. The dynamic stress could contribute to the compressive thermal stresses of the underlying columns to mutually create a fracture wave, if these columns had not been disintegrated still earlier by a fracture wave. The time of free fall of the upper structure for the height $h = 3.7$ m equals $\sqrt{2h/g} = 0.75$ s which is much greater than the time 0.05 s necessary to disintegrate the whole building by a fracture wave if it was created immediately after the tensile failure of cold bearing columns.

By the way, the authors of the "theory" missed the fact that the maximum dynamic stress would travel all the way down at the speed 5 Km/s and that the fracture wave of disintegration should immediately follow the shock wave of compression because no material could bear the "enormous" compression stress that was, according to the theory, 64.5 times greater than the static stress. And so, the "theory" supports the fracture wave mechanism of the collapses, not the progressive failure mechanism. But, what happened is more complicated than what implied by the "theory".

Beyond the present calculation of dynamic overload, there is direct evidence that it is the thermal, not dynamic, stress that triggered the collapse of the neighboring 47-story tower. A portion of spilled fuel got on the top of the latter building and set a fire there. There were no upper structure above to fall down and start the collapse as the "theory" claims. It is only the thermal stresses that could trigger a fracture wave of disintegration in this case.

4. Free fall: fracture wave vs. progressive failure

To explain the free fall regime of the collapses, the "theory" assumes that at any moment of collapse there are exist an upper part of the tower that moves down and an underlying structure that rests intact, and that the underlying structure produces no reaction and resistance to the falling upper part because “the inelastic energy dissipation in plastic hinges of collapsing columns is much less than the kinetic energy of the falling mass”.

This thesis is an evident blunder. The loss of kinetic energy of the falling mass is caused, mostly, by the elastic deformation of the underlying structure, and the resistance of a solid structure is due, mostly, to the elastic reaction that can stop the falling mass even if the inelastic energy dissipation is zero. For example, the “enormous” dynamic overload from the impact of the upper structure on the critical floor, which is according to the “theory” 64.5 times greater than the static load, should be also applied to the moving mass creating the force of resistance, by the Newton law, which is disregarded by the “theory”.

Even within the framework of progressive failure model, the inelastic energy dissipation was miscalculated. It is true that the energy dissipated in plastic hinges of buckling columns of the underlying structure is about 8.4 times less than the decrease of the gravitational energy of the upper structure falling down in the critical floor. However, it is valid with account of only one plastic hinge per column of one floor, which contradicts to the following facts. First, the dynamic instability of columns/bars occurs by higher order modes of buckling (the greater is the dynamic load, the higher is the mode of buckling). Secondly, the debris should be two-meter-long segments of columns, which is very far from the reality. The same calculation would predict the ratio 2.8, and not 8.4, if three plastic hinges per column of one floor would be taken into account. In this case the debris would be one-meter-long segments of columns, which is closer to the reality. Any accurate calculation would show that the inelastic energy dissipation during the collapse is significant and comparable with the decrease of gravitational energy and the value of the corresponding kinetic energy.

Let us analyze the model of “progressive failure” avoiding the mistakes of the “theory”. Suppose that all columns of the critical floor disappeared and the upper structure freely fell down on the underlying structure, as suggested in the “theory”. From the accurate solution of Section 3 it follows that the maximum total stress in the columns of the underlying structure from the impact is equal to 340 MPa which is almost twice less than the yield strength of steel. This value must be close to the buckling stress of well-designed columns, with account of the safety factor. Taking into consideration that 340 MPa is greatly exaggerated by the free fall assumption and that this maximum stress is kept for a quite short time much less than about 0.01 s, it is doubtful that this improvised impact could produce any fracture or failure in the columns of the underlying structure. The buckling failure could be possible only in the case of very flexible columns of a very bad design because the buckling stress of even flexible columns is several times greater for the dynamic load than that for the static load due to higher modes of buckling.

Hence, the progressive failure is nothing but a result of the miscalculations of the “theory”.

The only possible scientific explanation of the free fall regime of the collapses is that the buildings were disintegrated by fracture waves at the beginning of each collapse, which took about 0.05 s because fracture waves propagate at the speed about 6 Km/s in steel, glass, concrete, and marble. The disintegration by cracking is unnoticeable for such a short time because the volume of cracks is very small as compared to the volume of intact material, with no visible deformations during that time. The cracking of the tower for 0.05 s produced the sound emission heard as an explosion. A boom would be heard if the cracking took 10 s as suggested by the "theory" of progressive failure. For a fracture wave to propagate, a material should be loaded by compressive stresses of high energy because this energy is released in the fracture wave. (See Appendix 1).

The material velocity of fragments behind the fracture wave has an order of 10 to 100 m/s depending on material and stress; for glass it is about four times greater than for steel. The size of fragments behind the fracture wave depends on stress and material; for steel it is about 5 to 50 cm, and for glass, concrete and marble it is about 0.1 to 10 μm. Combination of free gravitational fall of heavy steel fragments and explosive sweep-away of particles of glass, concrete and marble in the form of dust clouds created the picture of the collapses observed on TV screens.

A classical example of the fracture wave action is a Batavian tear of glass. If one breaks a tiny tail on the Batavian tear, it explodes into a cloud of dust with a loud sound. It takes 10^{-5} s to pulverize a five-centimeter tear by a fracture wave and 10^{-2} s to create a one-meter cloud of micron-size particles of glass.

And so, the fracture wave mechanism of the WTC collapse and the collapse of the neighboring 47-story building is supported by the following facts:

(i) All buildings collapsed in free fall regime;
(ii) Each collapse was accompanied by a sound of explosion;
(iii) The size of steel fragments and dust particles of glass, concrete and marble corresponds to that calculated in the theory of fracture waves;
(iv) Dust particles created clouds expanded for several hundred meters.

5. Fracture wave vs. shock wave

Let us summarize the basic properties of shock waves and fracture waves following Cherepanov (1979). Both waves represent some fronts of discontinuity of material density, velocity, and stresses.

Shock waves are produced by impacts and explosions in gases, liquids, and solids. The density of material behind a shock wave is always greater than in front of the wave. The maximum compressive stress behind a shock wave is always greater than in front of the wave. The normal velocity of a shock wave is always greater than the speed of sound (in solids and liquids, slightly greater). The thickness of a shock wave is defined by viscous properties of a material.

It is a widely-spread but wrong belief that a shock wave can disintegrate a material into small fragments*. To disintegrate means to crack, but a shock wave cannot crack a solid because any cracking is accompanied by a dilatation of the solid. A fracture wave should always follow a shock wave in order to disintegrate a material.

Fracture waves can be produced only by compressive stresses in solids. Fracture wave separates an intact material in front of the wave from a destructed material behind the wave. The thickness of a fracture wave has an order of the size of material fragments behind the wave. The mean density of a material behind a fracture wave is always less than in front of the wave. The maximum compressive stress behind a fracture wave is always less than in front of the wave. The normal velocity of steady fracture waves is equal to the speed of sound (longitudinal elastic wave). For unsteady fracture waves, the

* Dr. Bazant and many anonymous referees have stuck to this opinion.

normal velocity is less than the speed of sound and determined from the solution of a particular problem, that is, depends on boundary and initial conditions.

6. Conclusions

It was shown that, in the tragic collapses on September 11, 2001:

(i) Creep played no part, and these were the thermal stresses that triggered the collapses;

(ii) Tensile failure of some cold bearing columns from the thermal stresses started the collapses, and not the creep buckling of hot columns;

(iii) Dynamic stress from the impact of the upper structure on the initial stage of each collapse was insufficient even to produce a failure of the underlying structure, not to say about a progressive failure of entire buildings;

(iv) A fracture wave, originated after tensile failure of some cold bearing columns in the critical floor, disintegrated each building for about 0.05 s and produced the sound of explosion, and steel fragments freely fell down while glass, concrete and marble fragments created dust clouds.

The fracture wave mechanism is the most plausible hypothesis because it is supported by the facts of the matter and by the accurate calculations. However, the exact conditions triggering fracture waves need to be studied which is a challenging problem for the future.

Acknowledgement

This author thanks the editors and anonymous referees of the technical journals that rejected the author's explanation because it contradicted to the official "theory". Their comments have stimulated this author to undertake the present analysis of the "theory" that many trust to so deeply.

References

1. Zdenek P. Bazant and Young Zhou (2002) Why did the World Trade Center collapse? - Simple analysis, *J. Engineering Mechanics*, Vol. 128, No. 1, p. 1-6. (See Appendix 2)
2. Genady P. Cherepanov (1979) Mechanics of Brittle Fracture, McGraw-Hill, New York, p. 1-980.

Appendix 1. The theory of fracture waves

The fracture wave is a front of discontinuity of mass density, material velocity and stresses that separates an intact material in front of the fracture wave from a destructed one behind. The mass density behind a fracture wave is always less than that in front of the wave because any cracking of a solid dilates it. The thickness of a fracture wave has an order of the size of fragments of the destructed material behind the wave.

The conservation laws on the fracture wave can be written as follows:

mass conservation

$$\rho_0(V - v_0) = \rho_F(V - v_F), \tag{A.1}$$

momentum conservation

$$-\sigma_0 + \rho_0(V - v_0)^2 = -\sigma_F + \rho_F(V - v_F)^2, \tag{A.2}$$

energy conservation

$$\frac{1}{2}(V - v_0)^2 + \frac{U_0}{\rho_0} - \frac{\sigma_0}{\rho_0} = \frac{1}{2}(V - v_F)^2 + \frac{U_F}{\rho_F} - \frac{\sigma_F}{\rho_F} + \frac{D}{\rho_F}. \tag{A.3}$$

Here: lower index 0 refers to the intact material in front of the fracture wave, lower index F refers to the destructed material behind the fracture wave, V is the normal velocity of the fracture wave, v is the material velocity normal to the fracture front, ρ is the material density, U is the volume density of elastic energy of the material, σ is the stress component normal to the fracture front, D is the volume density of surface energy of the destructed material.

Equations (A.1) and (A.3) can be re-written as follows:

$$\frac{1}{\rho_0} - \frac{1}{\rho_F} = \frac{1}{\rho_0}\frac{v_F - v_0}{V - v_0}, \tag{A.4}$$

$$\sigma_0 - \sigma_F = \rho_0(V - v_0)(v_F - v_0), \tag{A.5}$$

$$\frac{D}{\rho_F} = \frac{U_0}{\rho_0} - \frac{U_F}{\rho_F} + \frac{1}{2}(\sigma_0 + \sigma_F)\left(\frac{1}{\rho_F} - \frac{1}{\rho_0}\right). \tag{A.6}$$

Let us assume that the intact material is at rest, i.e., $v_0 = 0$. Then, the values of ρ_F, v_F and D can be found from equations (A.4) to (A.6) as follows:

$$\rho_F = \frac{\rho_0}{1 - \frac{\sigma_0 - \sigma_F}{\rho_0 V^2}}, \tag{A.7}$$

$$v_F = \frac{\sigma_0 - \sigma_F}{\rho_0 V}, \tag{A.8}$$

$$D = \frac{\rho_F}{\rho_0}\left(U_0 - \frac{\sigma_0^2 - \sigma_F^2}{2\rho_0 V^2}\right) - U_F \,. \tag{A.9}$$

From equations (A.7) and (A.8), it follows that $v_F < 0$ and $\sigma_0 < 0$ because $\rho_0 > \rho_F$ due to the physical meaning of the fracture wave. It means that the fracture wave can propagate only in a compressed material and the velocity of destructed material is always opposite to the normal velocity of the fracture wave.

Let us confine ourselves by steady fracture waves. Assume for a moment that $V < c$ where c is the speed of longitudinal elastic waves in the material. An elastic forerunning field ahead of such a fracture wave would also be steady-state. However, from the theory of elasticity it follows that steady elastic field can propagate only at the speed of c. (The shear wave is, evidently, impossible). It means the assumption is not valid, so that $V \geq c$ for steady fracture waves. From equation (A.7) it follows that ρ_F is very close to ρ_0, i.e. $\rho_F \approx \rho_0$ because $\sigma_0 << E$ and $\rho_0 V^2 \geq \rho_0 c^2 \approx E$. And so, equation (A.9) becomes

$$D = U_0 - \frac{\sigma_0^2}{2\rho_0 V^2} - \left(U_F - \frac{\sigma_F^2}{2\rho_0 V^2}\right). \tag{A.10}$$

Let us neglect the mutual contacts of fragments of the destructed material because of lost coherence, so that $\sigma_0 >> \sigma_F$ and $U_0 >> U_F$, and equations (A.8) and (A.10) take the form

$$v_F = \frac{\sigma_0}{\rho_0 V}, \qquad D = U_0 - \frac{\sigma_0^2}{2\rho_0 V^2} \,. \tag{A.11}$$

Let us analyze D as a function of V. Based on the principle of minimum of surface energy the value of D should be minimum possible because D is the surface energy of the destructed material in unit volume. From this principle, it follows that $V = c$, because D is minimal at $V = c$. In 1967, the same conclusion was derived by this author and Leo A. Galin based on the analogy between the fracture wave and detonation wave in TNT (the Chapman-Jouguet hypothesis).

And so, the basic equations of steady fracture waves can be summarized as follows:

$$V = c, \qquad D = U_0 - \frac{\sigma_0^2}{2\rho_0 c^2}, \qquad v_F = \frac{\sigma_0}{\rho_0 c}, \qquad \rho_F \approx \rho_0. \tag{A.12}$$

These equations are valid for any anisotropic, quasi-brittle materials whose dimensions are much greater than the thickness of the fracture wave, that is the size of fragments of the destructed material. Using the effective surface energy Γ of the cracking

of the material known from fracture mechanics tests, one can estimate the size of fragments of the destructed material in terms of Γ and D. E.g., one can find that:
if fragments are identical cubes with rib d,

$$d = 12\frac{\Gamma}{D}, \qquad \text{and} \tag{A.13}$$

if fragments are long identical needles of hexagonal cross-section with rib r,

$$2r = \frac{8}{\sqrt{3}}\frac{\Gamma}{D}. \tag{A.14}$$

The needle shape of fragments was observed in some experiments with glass specimens.

Suppose an isotropic material is in the state of hydrostatic compression by stress σ_0 in front of the fracture wave. In this case, we have

$$U_0 = \frac{3}{2}\frac{(1-2\nu)}{E}\sigma_0^2, \qquad \rho_0 c^2 = \frac{E(1-\nu)}{(1+\nu)(1-2\nu)}. \tag{A.15}$$

Here E and ν are Young's modulus and Poisson's ratio. Using equations (A.12) to (A.15) we get the following results for silicate glass at $\Gamma = 2$ N/m, $\rho_0 = 2.4$ g/cm^3, $E = 7\times10^4$ N/mm^2, and $\nu = 0.17$: $V = c = 5950$ m/s and
at $\sigma_0 = -500$ N/mm^2: $v_F = -35$ m/s, $D = 1.9$ N/mm^2, $d = 12.8$ μm, $2r = 5$ μm;
at $\sigma_0 = -1$ KN/mm^2: $v_F = -70$ m/s, $D = 7.5$ N/mm^2, $d = 3.2$ μm, $2r = 1.2$ μm;
at $\sigma_0 = -5$ KN/mm^2: $v_F = -350$ m/s, $D = 187.5$ N/mm^2, $d = 0.1$ μm, $2r = 0.05$ μm.

The glass needles in the range of $2r$ from about 1 μm to about 10 μm were observed experimentally, Cherepanov (1979). For rocks and building materials like concrete, marble, and wood the figures for v_F, D, d, and r are comparable to those in glass because their specific surface energy Γ is comparable with that of glass.

The dust produced by the collapses of three buildings on September 11, 2001 was created by micron-size fragments of glass, concrete and marble, in correspondence with these calculations because the thickness of fracture waves in these materials was much less than any structural dimension.

Suppose, now, that a fracture wave propagates in a steel column between the bottom and ceiling of a floor. Suppose that the column is a solid, vertical, round cylinder and that the steel fragments behind the fracture wave represent some segments of the column cracked along sliding planes inclined at 45° to the axis of the cylinder. In this case the height of the segment h_s is equal to

$$h_s = 2\sqrt{2}\,\frac{\Gamma}{D}\,, \tag{A.16}$$

and

$$U_0 = \frac{\sigma_0^2}{2E}\,, \qquad \rho_0 c^2 = \frac{E(1-\nu)}{(1+\nu)(1-2\nu)}\ . \tag{A.17}$$

Here σ_0 is the mean compressive stress in the intact segment in front of the fracture wave from gravitational, thermal and technological stresses (e.g. from rolling, welding, and assembling). The fracture wave releasing the potential energy of compressive stresses outstrips the group speed $\sqrt{E/\rho_0}$ so that at the distance of 4 m, the height of the column, it goes ahead by about 0.3 m.

Using equations (A.12), (A.16) and (A.17) one can find for steel: at $\Gamma = 20$ KN/m, $\rho_0 = 7.9$ g/cm^3, $E = 200$ GPa, and $\nu = 0.33$: $V = c = 5850$ m/s and
at $\sigma_0 = -1$ KN/mm^2: $v_F = -21$m/s, $D = 0.83$ N/mm^2, $h_s = 6.8$ cm;
at $\sigma_0 = -500$ N/mm^2: $v_F = -10$ m/s, $D = 0.2$ N/mm^2, $h_s = 27.2$ cm.

It should be noted that the effective surface energy Γ of steel includes the plastic energy dissipated in a thin layer on the crack surface. And so, the rough estimate of the size of steel debris based on the accurate energy balance in the fracture wave provides a realistic picture relevant to the collapses of all three buildings on September 11, 2001 because h_s is much less than the height of a column in a floor.

Another approach to the estimate of steel debris created during the collapses of the buildings is to model the building as a solid material volume of the same mass and shape, structurally orthotropic with vertical axis of symmetry and polar planes of symmetry, whose stiffness in these directions is equal to the stiffness of the building. The effective surface energy of this model material is equal to $(1-\varepsilon)^{\Gamma}$ where ε is the ratio of the empty space volume to the volume of the building, and Γ is the effective surface energy of steel. The propagation of fracture waves in porous materials requires a similar approach.

Appendix 2. The official "theory" (See the attachment "Bazant& Zhou.PDF")