ВЕСТНИК ЧГПУ
им. И. Я. ЯКОВЛЕВА
МЕХАНИКА
ПРЕДЕЛЬНОГО
СОСТОЯНИЯ
№ 1 • 2008

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A CRITICAL ANALYSIS OF THE GOVERNMENT'S THEORY: THE COLLAPSE OF THE NEW YORK TOWERS ON SEPTEMBER 11, 2001

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The generally-accepted explanation of the collapse of the World Trade Center towers in New York on September 11, 2001 is based on the speculative "theory" of progressive buckling of cold bearing columns at the speed of free fall triggered by creep buckling of the hot columns of the critical floor under the fire and by dynamic impact of the upper structure. In the present paper the basic assumptions and calculations of the "theory" are re-visited and examined. It is shown that the thermal stresses , not creep, played the main part , and the dynamic stresses from the collapse of bearing columns in the critical floor were much less than those calculated in the "theory". The "theory" cannot explain the free fall, explosion sound, and pulverization of the buildings. These facts of the matter can only be explained by fracture waves that disintegrated the towers, at least partially, just at the very beginning of each collapse. It is suggested that, consistent with all known facts of the matter, at least in the initial stage, heating of bearing columns and horizontal trusses in the "hot" spot caused high thermal stresses, both compressive and tensile, in the buildings, the thermal stresses combined with gravitational, technological, and dynamic stresses triggered a self-maintaining fracture wave, and the fracture wave disintegrated a substantial part of the entire building by invisible cracks 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 technical subjects, namely the theory of fracture waves, the problem of dynamic impact, and fracture waves in steel structures are treated in Appendices A, B, and C respectively.

The September 11 collapses have caused already two wars and millions of deaths. They deserve to be studied by science due to the unwillingness of governmental agencies of the US and other countries to undertake scientific and criminal investigations.

I. INTRODUCTION

The collapses of three tallest buildings in New York on September 11, 2001 aroused interest of engineering community to the unsolved problem of safety and destruction of man-made structures. While the general cause of the collapses—fire—has been generally recognized afterwards, it was not known to experts before the collapses; no people were evacuated during the fire and 330 firemen sent to extinguish the fire died together with about 1500 people in the buildings. Evidently, the collapse of this steel structure from fire was hard to foresee because the pulverization failure mode of steel structures has, never before, been observed in practice or any tests commonly resulted in few broken parts. Nevertheless, the official "theory" first published and substantiated in[1] appeared on the next day after the collapses. It has never been examined; moreover, NIST engineers made a numerical model on this "theory". The general conclusion derived was that the collapses were unavoidable as a result of the fire[1], contrary to the pre-fire judgment.

According to the "theory" the bearing columns of the critical floor under the fire collapsed from high-temperature creep buckling and the upper structure fell down producing an enormous dynamic load, 64 times exceeding the static one, that crashed the underlying structure in the progressive buckling regime. In what follows the basic assumptions and calculations of the "theory" are re-visited and examined. It is shown that the thermal stresses, not creep, played the primary role and that the dynamic load from impact was much less than that calculated by Bazant[1]. The "theory" cannot explain the free fall regime of the collapses, pulverization of the buildings, and explosion sound from the collapses. The only scientific explanation of all these facts of the matter is that self-maintaining fracture waves disintegrated the buildings by invisible cracks just at the very beginning of each collapse[2] providing the necessary conditions for the free fall of the top part of the buildings. It is only self-maintaining fracture waves that could pulverize a good deal of the entire solid structure. All other failure modes studied in fracture mechanics and materials science are characterized by the separation of a structure into two or few parts. The self-maintaining fracture waves pulverized the WTC towers and the adjacent 47-story building like the detonation wave does a TNT piece or the flame does a fuel. It should be noted that common fracture waves of the explosion and penetration mechanics, although maybe relevant, are not considered here.

Moreover, if we accept the theory of progressive failure as NIST and the American/British scientific establishment did, the strict Newton's –law—based analysis of progressive failure leads to the conclusion that all collapses started on the floors located significantly lower than the floors hit by terrorists and subjected to fire.

II. 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"[1], the "theory" says, when paying no attention to thermal stresses, combustion of spilled fuel in the critical floor, and residual technological stresses arisen from rolling, welding, and assembling.

Let us verify the basic assumptions of this "theory". First, the loss of the protective thermal insulation of more than half of the 260 columns of the critical floor by the aircraft impact is nothing but a miracle because the aircraft was very small compared to the horizontal dimension of the floor. Also, 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 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. For details of the calculation, see pp.120-123 in the reference textbook[3]. 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 too arbitrary. 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 (see Problem 11.38 on p.587 in the reference textbook[4]). One can find that the combustion products leave the combustor for the turbine at the temperature 769°C (see p.754 in same text for this answer), 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 some aircrafts.

Let us compare the combustion of the fuel spilled in the critical floor with the combustion of this fuel in the aircraft 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 aircraft 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 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 has to be at a high temperature for a long time.

Thirdly, the decrease of the yield strength of steel was too little to play a significant 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 to ten times less than the yield strength. Some possible phase transitions in steel at this temperature causing creep require time, well not sufficient under the circumstances as explained above.

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 and adjacent horizontal trusses of the ceiling 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 under the conditions of total constraint 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 unrealizable.

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 floor trusses and cold columns of framed tube, penetrated far into cold columns and trusses of the upper and underlying structure. Combined with gravitational and residual technological stresses, the compressive thermal stresses inside the building created a heating bomb, so that a fracture wave was born that disintegrated a good deal of the entire tower for less than 0.1 s.

For a comparison, a Batavian tear[5] 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 A). This failure mode is similar to the pulverization of the WTC towers. Also, as a reminder, the compressive residual stress from rolling in steel columns can achieve a half or more of the yield strength. For the discussion of fracture waves in steel structures, see Appendix C.

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°C 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, whose bottom had the vaporization temperature of fuel, i.e. less than 100°C, while mean temperature on the top of flames, at the ceiling, could certainly achieve 800°C and much higher due to high adiabatic flame temperature of octane. A linear approximation leads to about one meter long column top part under temperature 550°C 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

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

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

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

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 hot 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

$$\beta_b = 1 - \frac{(f_o - f)\sigma_Y}{\delta\alpha ET}, \quad (6)$$

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

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

From equation (7) it follows that

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

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 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, even more probable because of thermal extension and possible failure of hot horizontal trusses, started the process of release of elastic energy of compressive stresses that occurred in a self-maintaining fracture wave because it is only the fracture wave that can pulverize material.

III. 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[1]. "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 (see Appendix B for technical details):

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

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

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:

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

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

The maximum stress is equal to:

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

If the assumption of the "theory" about free fall of the upper structure is accepted, that is all bearing columns of steel in the critical floor suddenly disappeared, 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 (of the order of pressure produced by high heels of a girl). The approximate estimate of the "theory" is very inaccurate.

However, even the maximum stress 340 MPa from the impact is still about six times less than the maximum possible thermal stress 2 GPa. Besides, the maximum stress 340 MPa is greatly exaggerated. If we take into account that the falling mass (projectile) is not concentrated but distributed in a bar similar to the subject column, the maximum stress becomes twice less (Appendix B). Further, even more significant decrease of the maximum dynamic stress is due to the residual resistance of buckling hot columns in the critical floor. 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, at least, $\sqrt{2h/g} = 0.75$ s which is much greater than the time 0.1 s necessary to disintegrate the whole building by a self-maintaining fracture wave if it was created immediately after the tensile failure of cold bearing columns (see Appendices A and C).

By the way, the maximum dynamic stress traveled all the way down at the speed of longitudinal elastic waves in the steel framework of the WTC tower so that the fracture wave of disintegration would immediately follow the shock wave of "enormous" compression because no material could bear the "enormous" load. And so, if applied consistently, the "theory" would support the fracture wave mechanism of the collapses, not the progressive failure mechanism.

Using equations (11) and (12) we can analyze the comparative role of static, mg/S, and dynamic, VE/c, stresses in this event. If VE/c is greater than mg/S, which may be true if the critical floor was close to the top of the tower, the maximum dynamic stress at $t = 0$ can be greater than the static stress and tends exponentially to the static stress as time elapses. However, if VE/c is less than mg/S, which is surely true if the critical floor was far from the top of the tower, as it follows from the pictures of the collapses, the maximum dynamic stress at $t = 0$ is less than the static stress and tends exponentially to the latter as time grows. And so, the maximum dynamic effect from impact occurs from initial collapse of the top floor, and it is negligibly small for the impact of a heavy upper structure, contrary to the implication of the “theory”.

IV. 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”[1].

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” using more accurate analysis of dynamics. 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 Section 3 it follows that the maximum total stress in the columns of the underlying structure from the impact is less than 170 MPa which is, at least, four times less than the yield strength of steel, or the buckling stress of well-designed columns. Taking into consideration that 170 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 from the impact could be possible only in the case of very flexible columns of a very bad design, if the critical floor was close to the top of the tower, 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.

Moreover, even if we accept that the resistance of the underlying , intact structure to the motion down of the upper structure is zero, the acceleration of the falling mass appears to be significantly smaller than the gravitational acceleration so that free fall can’t be explained within the framework of progressive failure unless we accept that the collapses started on the floors located significantly lower than the floors hit by planes which leads to some premeditated collapses ,not tied to terrorists' planes, the conspiracy theory we refused to accept from the very beginning.

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

The only possible 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 0.1 s because fracture waves propagate at the speed of longitudinal elastic waves in steel, glass, concrete, and marble (see Appendices A and C). 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 0.1 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 Appendices A and C).

The initial velocity of fragments behind the fracture wave has an order of 10 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 has an order of one meter, 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[5]. 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 of 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 the pulverization of the buildings and 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.

Fracture waves have never, before the WTC collapse, been observed in steel structures. Let us explain why. The fragments of steel behind a fracture wave have an order of one meter (see Appendix C). It means that the size of the steel structure has to be much larger. The WTC collapse is so far the only known case of destruction of such a large steel structure from compressive stresses.

V. FRACTURE WAVE VS. SHOCK WAVE

Let us summarize the basic properties of shock waves and fracture waves [5]. 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, which is common in explosion and penetration mechanics.

Self-maintaining fracture waves can be produced only by high compressive stresses in solids, typically under triaxial compression (Appendices A and C). Fracture wave separates an intact material in front of the wave from a destructed material 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 longitudinal elastic waves (Appendices A and C). For unsteady fracture waves observed by explosions and impacts, the normal velocity is less and determined from the solution of a particular problem, that is, depends on boundary and initial conditions.

VI. CONCLUSIONS

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

(i) Creep played secondary role, 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 to produce a failure of the underlying structure;

(iv) A self-maintaining fracture wave, originated after tensile failure of some cold bearing columns in the critical floor, disintegrated, at least, a significant part of each building for about 0.1 s and produced the sound of explosion, and steel fragments fell down in the free fall regime while fragments of glass, concrete and marble created dust clouds.

The exact conditions triggering fracture waves in very large steel structures need to be studied which is a challenging problem for the future.

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APPENDIX A. 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 conservation laws on the fracture wave can be written as follows:
mass conservation

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

momentum conservation

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

energy conservation

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

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) to (A.3) can be re-written as follows:

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

$$\sigma_0-\sigma_F=\rho_0\left(V-v_0\right)\left(v_F-v_0\right), \quad \text{(A.5}$$

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

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:

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

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

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

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, typical for self -maintaining destruction. 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 by 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[5]).

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 and the size of fragments of the destructed material. It should be noted that an account of comparatively minor residual stresses behind a fracture wave leads to a simple modification of eqns.(A.12), with no significant effect on calculation results. 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., for the two fracture modes one can find that:
if fragments are identical cubes with rib d,

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

and 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[5].

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

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

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[5]. 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.

APPENDIX B. THE PROBLEM OF DYNAMIC IMPACT

Suppose a concentrated 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. Let t be the time from the moment of impact $t = 0$ and x be the coordinate along the column located at $x \geq 0$. The impact produces the field of the dynamic stress $\sigma_x(x,t)$ and displacement $u(x,t)$ in the column that can be found from the following boundary value problem:

$$\frac{\partial^2 u}{\partial t^2} = c^2 \frac{\partial^2 u}{\partial x^2} \quad \text{for } ct > x > 0, \tag{B.1}$$

$$m\frac{dv_x}{dt} = S\sigma_x + mg \quad \text{when } x = 0, \tag{B.2}$$

$$u = 0 \quad \text{when } x \geq ct, \tag{B.3}$$

$$v_x = V_o \quad \text{when } x = 0, \quad t = 0. \tag{B.4}$$

Here:

$$\sigma_x = E\frac{\partial u}{\partial x},\ v_x = \frac{\partial u}{\partial t},\ c^2 = \frac{E}{\rho}, \tag{B.5}$$

E is Young's modulus, ρ is the material density, S is the column cross-section area, and c is the speed of elastic waves in the column.

The general solution $u = F_1(x-ct) + F_2(x+ct)$ to the wave equation (B.1) turns into $u = F_1(x-ct) - F_1(0)$ to meet the boundary condition eq. (B.3). And so, using eqs. (B.5) we find:

$$\sigma_x = EF_1'(x-ct),\ v_x = -cF_1'(x-ct), \tag{B.6}$$

where $F_1(\xi)$ is an arbitrary function of ξ that can be found from the differential eq. (B.2) and initial condition eq. (B.4) as follows:

$$F_1'(\xi) = -\frac{mg}{S} + \left(-\frac{V_o}{c} + \frac{mg}{SE}\right)\exp\left(\frac{SE}{mc^2}\xi\right). \tag{B.7}$$

Equations (9) and (10) in the main text immediately follow from eqs. (B.6) and (B.7).

To estimate the effect of a distributed mass suppose that the falling mass is a half-infinite elastic bar moving down at the speed V_o. Designate by E_p, S_p, ρ_p, and c_p the corresponding constants of this bar (subscript p stands for projectile) and $\sigma_x^+(x,t)$ and $v_x^+(x,t)$ the dynamic stress and material velocity in the projectile. One can find that:

$$v_x = V\,,\ \sigma_x = -E\frac{V}{c} \text{ when } ct > x > 0\,, \tag{B.8}$$

$$v_x^+ = V\,,\ \sigma_x^+ = -E_p\frac{SE}{S_pE_p}\frac{V}{c_p} \text{ when } 0 > x > -c_pt\,, \tag{B.9}$$

where

$$V = V_o\left(1 + \frac{c_p}{c}\frac{ES}{E_pS_p}\right)^{-1}. \tag{B.10}$$

Particularly, when the projectile is a rigid bar so that $E_pS_p >> ES$, we get

$$V = V_o\,,\ v_x = V_o\,,\ \sigma_x = -E\frac{V_o}{c}\ \ (ct > x > 0), \tag{B.11}$$

which coincides with the maximum stress and velocity in the column at $x = 0$ and $t = 0$ in the case of the concentrated mass m.

When $c_p = c$ and $E_pS_p = ES$ which is valid, e.g., if the projectile is the same as the column, we get

$$V = \frac{1}{2}V_o\,,\ v_x = \frac{1}{2}V_o\,,\ \sigma_x = -\frac{1}{2}E\frac{V_o}{c}. \tag{B.12}$$

Hence, with the account of elasticity of distributed mass of the projectile the dynamic stress becomes twice less.

APPENDIX C. FRACTURE WAVES IN STEEL STRUCTURES

Self-sustaining steady fracture waves can propagate in solid bodies subjected to triaxial compression of high elastic energy. Under triaxial compression all materials are capable to endure much higher compressive stresses than under biaxial or single-axial compression. If a plane in such a metastable, compressed body is released from stress, the material near the plane gets destructed, and a fracture wave can arise that transforms the metastable stressed state of the intact material into a stable, unloaded, condition of the destructed material. Fracture wave is the front where this transition occurs. The driving force of the fracture wave is the excessive elastic energy of the intact material.

Let us show that a self-maintaining steady fracture wave cannot propagate along a bar axially compressed by stress σ_o. Indeed, in this case equation (A.12) yields

$$D = U_o - \frac{\sigma_o^2}{2\rho_o c^2} = 0 \text{ because } U_o = \frac{\sigma_o^2}{2E} \text{ and } c^2 = \frac{E}{\rho_o}. \qquad \text{(C.1)}$$

A bar cannot accumulate an excessive elastic energy necessary for the steady propagation of fracture wave, so that bars are destructed in unsteady regimes.

However, in a plate biaxially compressed along its plane by stress σ_o a self-maintaining steady fracture wave can propagate. Indeed, in this case

$$U_o = \frac{1-\nu}{E}\sigma_o^2,\ c^2 = \frac{E}{\rho_o\left(1-\nu^2\right)}, \qquad \text{(C.2)}$$

and equation (A.12) yields

$$D = U_o - \frac{\sigma_o^2}{2\rho_o c^2} = \frac{(1-\nu)^2}{2E}\sigma_o^2. \qquad \text{(C.3)}$$

And so, under biaxial compression a plate can accumulate some excessive elastic energy necessary for the self-maintaining steady fracture waves.

Suppose a steady fracture wave propagates in a solid space of steel. Typical values of constants for steel are: $\Gamma = 20$ KN/m, $\rho_o = 7.9$ g/cm^3, $E = 200$ GPa, $\nu = 0.3$. Using eqs. (A.12) and (A.15) one can find: $V = c = 5500$ m/s, and

at $\sigma_o = -1$ KN/mm^2: $D = 1.14$ N/mm^2, $d = 21$ cm, $v_F = -20$ m/s,

at $\sigma_o = -500$ N/mm^2: $D = 0.29$ N/mm^2, $d = 82$ cm, $v_F = -9$ m/s.

Since the fragments of destructed steel have the dimension of an order of one meter, the thickness of the fracture wave in solid steel is measured by meters, so that the size of steel specimens has to be much larger than one meter. Hence, steady fracture waves in solid steel cannot be observed in laboratory conditions.

However, large-scale steel structures represent a complex architectural framework of bars, columns, beams, trusses that create shape and support like cohesion forces keep atoms fixed in crystals. The continuum mechanics approach assumes such a complex structure to be a solid continuum. We apply this approach to the WTC tower. Let us consider a homogeneous isotropic elastic body whose shape is exactly same as the WTC tower, with the material density ρ_b, Young's modulus E_b and shear modulus G_b of the body being determined as follows:

$$\rho_b S_b = \rho_o S_A,\ E_b S_b = E S_A,\ G_b S_b = G S_A. \qquad \text{(C.4)}$$

Here: S_b is the area of the critical floor; ρ_o, E, and G are the density, Young's modulus and shear modulus of steel in bearing columns of the tower; and S_A is the total cross-section area of all columns of critical floor. Equations (C.4) mean that the compression and shear stiffness of the continuum material are equal to the corresponding stiffness of the critical floor and that the density of the body is an average value defined similarly to porous materials.

For the sake of simplicity we assume that ρ_b, E_b and G_b defined by the critical floor will be the same for any floor (which is strictly valid only for equistrong tower designs). The similar assumptions are used when a steel specimen being considered an elastic continuum. As a reminder, the mass of steel is concentrated in nucleons of very small volume (e.g., the WTC tower can be compressed into a particle visible only by microscope).

Let us find Poisson's ratio ν_b and the speed c_b of longitudinal elastic waves in this elastic continuum using equations (A.15) and (C.4)

$$1+\nu_B = \frac{E_b}{2G_b} = \frac{E}{2G} = 1+\nu\ , c_b^2 = \frac{E_b(1-\nu_b)}{\rho_b(1+\nu_b)(1-2\nu_b)} = \frac{E(1-\nu)}{\rho_b(1+\nu)(1-2\nu)} = c^2\,. \qquad \text{(C.5)}$$

Hence, $\nu_b = \nu$ and $c_b = c$, that is Poisson's ratio and the speed of longitudinal elastic waves in this continuum coincide with those values for solid steel ($\nu = 0.3$ and $c = 5500$ m/s).

From here and the continuum model of the WTC tower, it follows that the self-maintaining steady fracture wave traveled in the WTC tower at the speed $V = c = 5500$ m/s. Since the characteristic size of fragments behind fracture wave in solid steel is about one meter, it is reasonable to assume that the thickness of the fracture wave in the WTC tower was about the height of the floor or even several floors. To estimate the size of steel fragments behind the fracture wave in the WTC tower we assume that they represent some segments of bearing columns cracked along sliding planes inclined at 45° to the axis of the column supposed to be a solid, round cylinder.

The energy dissipated by the creation of the segments of height h, is equal to $2\sqrt{2}\pi r^2\Gamma$ in terms of effective surface energy or $\pi r^2 D h_s$ in terms of effective volume density of dissipated energy. From here, it follows that

$$h_s = 2\sqrt{2}\,\frac{\Gamma}{D}\,. \qquad \text{(C.6)}$$

Suppose σ_o is the compressive stress in the intact column in front of the fracture wave from gravitational, thermal, dynamic, and technological stresses (e.g., from rolling, welding, and assembling). Equation (A.12) yields in this case

$$D = U_o - \frac{\sigma_o^2}{2\rho_o c^2} = \frac{0.9\sigma_o^2}{7E} \text{ because } \nu = 0.3,\ U_o = \frac{\sigma_o^2}{2E}\,. \qquad \text{(C.7)}$$

Using eqs. (C.6) and (C.7) for $E = 200$ GPa and $\Gamma = 20$ KN/m one can find:
at $\sigma_o = -1$ KN/mm^2: $D = 0.64$ N/mm^2, $h_s = 8.8$ cm,
at $\sigma_o = -500$ N/mm^2: $D = 0.16$ N/mm^2, $d = 35.2$ cm.

It should be noted that the speed of the fracture wave has no direct correlation with the speed of growth of isolated cracks   which is demonstrated by Figure C1. For isolated tensile cracks, the limiting speed is Rayleigh speed, and for shear cracks like those on Figure C1 the limiting speed is the speed of shear elastic waves[5]. However, the factual speed of the crack growth is usually much less than the limiting speed so that the thickness of the fracture wave in the WTC tower was much greater than the size of steel fragments as demonstrated by Figure C1.

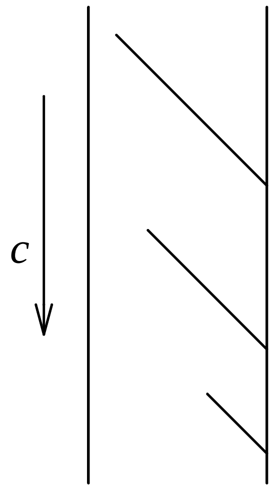

FIG C1. A plausible structure of the fracture wave in a column

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Received: December 19, 2007