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COLLAPSE OF TOWERS AS APPLIED TO SEPTEMBER 11 EVENTS

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The subject of the paper is the collapse of towers and highscrapers, particularly, the collapse of the World Trade Center towers in New York on September 11, 2001. The deduced equations of progressive collapse are used to refute the generally accepted opinion of experts about progressive collapse of the WTC towers in the free-fall regime, which is the official version of the US government. It is proved that progressive collapse is much slower than free fall. The critical floors where collapses started from are estimated using the well-established fact of the free-fall time of all WTC collapses. To this end, the most comprehensive "hybrid" analysis is advanced taking into account that collapses could start on several floors simultaneously, not on one floor as suggested before. According to this "hybrid" model, at the first stage, several floors collapsed simultaneously as a result of fracture waves causing a dust cloud and, at the second stage, the lower part of tower being intact in the first stage collapsed in the regime of progressive failure. Five different collapse types are studied, including the fastest and slowest collapses, and then the hybrid mode is examined with initial collapse of several floors followed by the "domino-effect" of the remaining floors. It is established that the floors where the WTC collapses started from were located significantly lower than the floors hit by the terrorists and subjected to fire. This conclusion confirms the same former result obtained by using the simple official theory of pure progressive collapse.

Progressive failure was the common mode of all collapses of tall buildings as emphasized by Bazant and Verdure [1]. In an earlier paper by Bazant and Zhou [2] they expressed the belief of civil engineers of the world that progressive failure runs in the free-fall regime, which seemed to have supported the government version of the New York collapses because of the well-known observation of the free fall-time of all collapses.

According to the government version, each of these collapses represented a simple progressive failure caused by the following chain of bad events: the crush of the terrorist plane into a critical floor set fire, severed 13% of the total of 287 steel columns, and stripped fire insulation from all columns that collapsed in one hour from creep buckling, which triggered the start of general progressive collapse by buckling floor-by-floor down to the ground. Bazant and Verdure [1] indicated that the towers would have survived if not all fire insulation had been stripped. The National Institute of Standards studied column fragments in the rubble and established that all fire insulation had been stripped, but I think it was stripped during the collapse and not by terrorists.

The government theory of progressive failure proves to be inconsistent with all facts and observations at the initial stage of the collapses. However, at the final stage, it is well-confirmed by visual observations which show the progressive-failure front marked by a dust cloud moving down onto the intact structure.

An alternative theory by Cherepanov [3] suggests that fracture waves disintegrated the towers at the very beginning of each collapse. The theory contradicts the visual observation of progressive-failure front at the final stage of the collapses, although it well explains dust, explosion sounds, and the free-fall time of all three collapses. In addition, in [4], Cherepanov has proved that the acceleration of progressive failure is much lower than the gravitational acceleration so that progressive failure is much slower than free fall which refutes the earlier

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belief of civil engineers that progressive failure is free fall, see [2]. (The report [1] with a new unsuccessful attempt to explain free fall represents a response to the article [4] sent to Dr. Bazant in January, 2006.)

Failure/fracture waves/ fronts are exposed and well-observed by dust clouds created by fracture waves by pulverizing concrete, glass, marble etc. When we observe dust clouds in collapses, we observe the work of fracture waves. A dust cloud is the marker of a fracture wave. Buckling or any other mode of failure cannot produce dust. When a car moves on a dusty road, its position is located by the front of moving dust. The failure front when a tower collapses can also be observed by a dust cloud. According to the well-known pictures of collapses of the New York towers, a dust cloud was instantly created at the beginning of each collapse, which covered a considerable part of the tower, with the lower part of the tower being intact. In a while, the lower front of dust cloud moved down marking the front of progressive failure.

In what follows, we study five characteristic modes of progressive collapse and then introduce a hybrid mode that explains all available facts mentioned above.

Progressive Failure: Critical-Floor Effect

Let us study progressive failure of a tower of height H_0. Very many different modes of progressive failure are possible depending, in particular, on the position of a critical floor where a collapse starts from. Let us illustrate this point by five specific modes using the equations of progressive collapse deduced in [4], with the rubble size being ignored. For the sake of simplicity and clarity, its is also assumed that the mass of the tower is uniformly distributed along the vertical and the resistance of the underlying intact structure to the motion of the upper mass falling down is zero. These assumptions allow us only to provide a very conservative estimate of the critical floors where collapses start from. The account of finite resistance and the actual nonuniform mass distribution in the towers leads to the critical floors located much lower than the floors following from this estimate, because finite resistance and the actual nonuniform mass distribution slow down the collapse process, see [5], and [6].

The Top Floor is Critical. In this case, the equations of progressive failure are as follows [5]:

$$\frac{dM}{dt} = m\frac{dx}{dt}, \qquad \frac{d}{dt}\left(M\frac{dx}{dt}\right) = Mg \qquad \left(m = \frac{M_0}{H_0}\right). \tag{1}$$

Here, $g = 9.8\,\mathrm{m/sec}$, t is time, x is the vertical coordinate positioning the front of progressive failure and directed downward, so that the top of the tower corresponds to $x = 0$ and the ground floor to $x = H_0$, M is the mass of the upper structure that moves down under the gravity force and increases with time (because it absorbs the underlying structure), M_0 is the mass of the whole tower, and m is the mass of the tower per unit length assumed to be constant just for the purpose of getting some exact conservative estimate.

Under the natural initial conditions

$$M = 0, \qquad \frac{dx}{dt} = 0 \quad \text{when} \quad t = 0, \tag{2}$$

the solution of equations (1) is very simple:

$$M = \frac{1}{6}mgt^2, \qquad x = \frac{1}{6}gt^2. \tag{3}$$