Why Did the World Trade Center Collapse?

Each tower of the World Trade Center was designed to withstand, as a whole, the horizontal impact of a large commercial aircraft. Why, then, did total collapse occur?

Zdeněk P. Bažant, Walter P. Murphy Professor of Civil Engineering and Materials Science at Northwestern University, and Yong Zhou, a graduate research assistant at Northwestern, suggest that the collapse was the dynamic consequence of the prolonged heating of the steel columns to very high temperatures. Such heating would have caused creep buckling of the columns of the framed tube along the perimeter of the structure that transmitted the vertical load to the ground. They offer the following as a likely scenario of the failure.

In stage 1 (see Figure 1), the conflagration caused by the aircraft fuel spilled into the structure causes the steel of the columns to heat to temperatures apparently exceeding 800°C (far higher than those of the standard fire of the American Society for Testing and Materials). The heating is probably accelerated by loss of the protective thermal insulation of the steel during the initial blast. When heated to such temperatures, structural steel exhibits significant creep (i.e., a slow increase of deformation under load), and its yield limit decreases significantly. Thus, the effective stiffness of the columns is greatly reduced, and, as a result, many columns buckle (stage 2), losing their load-carrying capacity as a consequence.*

Once more than about half of the columns in the floor that is heated the most (the critical floor) have buckled (stage 3), the weight of the structure above this floor can no longer be supported; the upper part then begins to fall onto the lower part, below the critical floor, gathering speed until it hits the top of the columns of the underlying floor. At the moment the upper part has moved down through the height of the floor, it has an enormous kinetic energy and a significant downward velocity. The vertical impact of the upper part falling onto the lower part generates vertical loads much higher than the load capacity in the columns of the underlying floor (stage 4), even if these columns have not been heated. The columns of the lower floor thus buckle, too. Progressive buckling under subsequent dynamic impacts then proceeds downward, floor by floor.

Figure 1. *The five stages in the authors' failure scenario.*

The details of the progression to failure after the decisive initial trigger that sets the upper part of the structure in motion are of course more complicated. The upper part of the structure, for example, tilts as it falls; furthermore, because the structure is a framed tube with floor beams of large spans, the impacted floors may collapse ahead of the tube, thus depriving the tube wall of its lateral support against global buckling. Regardless of these and other details, however, we can make the following two simple and crude estimates of the overload ratio of the columns of the floor just below the critical floor that triggered the catastrophic chain of events.

A short time after the vertical impact of the upper part, but after the wave caused by the vertical impact has propagated downward, the lower part of the structure can be considered to act approximately as a vertical spring (see Figure 2). For this estimate, we neglect the energy dissipation, particularly that due to the buckling of columns; in addition, the gravitational potential energy lost by the upper part in its downward displacement from the initial equilibrium position to the point of maximum deflection of the lower part, which is considered to behave elastically, is equated to the strain energy of the lower part. In this way, we obtain the equation $mg[h + (P/C)] = P^2/2C$. Its solution $P = P_{dyn}$ yields the following overload ratio from the impact of the upper part:

Figure 2.

$$P_{dyn}/P_0 = 1 + \sqrt{1 + (2Ch/mg)} \approx 31.$$

Here h = height of the critical floor columns (i.e., height of the initial drop of the upper part of the structure) ≈ 3.7 m; m = mass of the upper part $\approx 5.8 \times 10^7$ kg; C = spring constant of the lower part in axial compression $\approx 7.1 \times 10^{10}$ N/m; g = gravity acceleration; and $P_0 = mg$ = design load capacity. The input numbers are estimates for the north tower, based on the typical properties of buildings of this type.

The second simple and crude estimate of the initial overload ratio at the moment of impact is:

$$P_{dyn}/P_0 = (A/P_0)\sqrt{2\rho g E_{ef} h} \approx 64.5,$$

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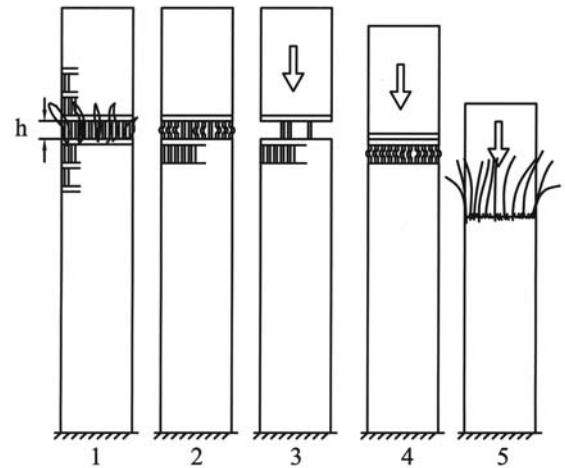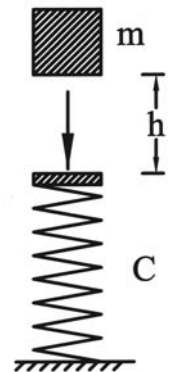
*Although small-deflection buckling does not cause a drop in the vertical load capacity of columns, large viscoplastic deflections cause it to drop virtually to zero.

where A = cross-sectional area of the building, E_{ef} = cross-sectional stiffness of all columns divided by A, and ρ = specific mass of the building per unit volume. This estimate is calculated from the elastic wave equation, which yields the intensity of the step front of the downward pressure wave caused by the impact if the velocity of the upper part at the moment of impact on the critical floor is considered as the boundary condition.

The latter estimate gives the initial overload ratio, which exists for only a small fraction of a second at the moment of impact. After the wave has propagated to the ground, the former estimate is appropriate.

In spite of the approximate nature of this analysis, it is obvious that the elastically calculated forces in the columns caused by the vertical impact of the upper part must have exceeded the load capacity of the lower part by at least an order of magnitude.