Mechanics of Collapse of WTC Towers Clarified by Recent Column Buckling Tests of Korol and Sivakumaran

Jia-Liang Le[1], **and Zdeněk P. Bažant**[2]

Abstract: The previously formulated model of the gravity-driven collapse of the twin towers of the World Trade Center on 9/11/2001 was shown to match all the existing observations, including the video record of the crush-down motion of the top part of tower during the first few seconds, the seismically recorded duration of collapse, the size distribution of particles caused by impact comminution of concrete floor slabs, the loud booms due to near-sonic lateral ejection velocity of air and dust, and precedence of the crush-down collapse mode before the crush-up. Nevertheless, different degrees of ductility, fracturing and end support flexibility of WTC columns could lead to an equally good match of these observations and remained uncertain, due to lack of test data. Recently, Korol and Sivakumaran reported valuable experiments that allow clarifying this uncertainty. They reveal that, under the assumptions of rigid end supports and unlimited ductility (or no fracturing), the energy dissipation in the WTC columns would have been at maximum 3.5-times as large as that calculated by the plastic hinge mechanism normally considered for small deflection buckling. This increase would still allow close match of all the aforementioned observations except for the first two seconds of the video. The proper conclusion from Korol and Sivakumaran's tests, based on close matching of the video record, is that the fracturing of columns and the flexibility of end restraints must have significantly reduced the energy dissipation in columns calculated under the assumptions of no fracture and no end restraint flexibility.

Keywords: Buckling, Collapse, Ductility, Fracture

Introduction

Previous studies [4, 3, 2, 6] led to a rigorous mathematical model which showed that a gravity driven collapse of the twin towers of the World Trade Center (WTC) in New York on 9/11/2001 was inevitable. The model showed that, at the beginning of collapse, the energy dissipation by plastic buckling of columns was the main mechanism of resistance. It also explained why the crush-down must have preceded the crush-up, and why air and debris were ejected laterally at almost the sound velocity, inevitably making loud booms and big dust clouds. It gave the correct size distribution of the particles from impact comminution of the concrete floor slabs, and agreed closely with the observed duration of collapse. Further it explained why the towers did not topple sideway like a tree [4], and why the motion observed in the initial video was virtually smooth, without any velocity fluctuation detectable by eye [6]. However, for lack of test data, it left unanswered two questions: 1) Didn't extensive fracturing of the columns limit significantly the ductility of steel? And 2) didn't flexibility and plasticity of the spandrel plates reduce the rotations, and thus the energy dissipation, in the plastic hinges at column ends? And if so, by how much?

Korol and Sivakumaran [5] recently presented valuable experimental results that allow answering these questions. They tested reduced-scale extruded H-shaped aluminum columns without end restraints which exhibited virtually unlimited ductility, i.e., no fracture. They found that the dissipation by a 180° rotation of the plastic hinge at mid height of the column was about 3.5-times as large as that calculated in [4] by extrapolating from small rotations the work of plastic bending moment acting on a planar cross section. This extrapolation ignored the local buckling and folding of column flanges, and large tensile flange extension, as revealed by these tests (Fig. 1).

[1]Associate Professor, Department of Civil, Environmental, and Geo- Engineering, University of Minnesota, Minneapolis; Email: jle@umn.edu.

[2]Distinguished McCormick Institute Professor and Walter P. Murphy Professor, Department of Civil and Environmental Engineering, Northwestern University, Illinois; Email: z-bazant@northwestern.edu; Corresponding author.

a) b) c)

Figure 1: Experiments by Korol and Sivakumaran: a)-b) specimen during the test, and c) final deformation shape of the specimen (Source: Fig. 3 and Fig 7a in Korol Sivakumaran [5]).

Simplifications of Original Analysis Due to Lack of Data

Because of uncertainties due to lack of experimental data, the original analysis of WTC collapse [4, 3] introduced three simplifying assumptions:

a) perfect ductility of steel, with no fracture,

b) constancy of the bending moment in the plastic hinge up to 180° rotation, and

c) rigid support of column ends.

With these assumptions and for the plastic bending moment based on the standard engineering theory of bending [7, Sec.8.6] (with the cross section remaining planar), it was found that the energy, W_d, dissipated by buckling of the columns of the first collapsing floor represented about 1/8 of the kinetic energy $Mv_0^2/2$ of the impacting mass M of the upper part of tower [4], v_0 being the impact velocity (0.19 m/s). According to these original assumptions, the buckling of the columns of the first impacted floor reduces the kinetic energy to $Mv_1^2/2 = (1 - \frac{1}{8})Mv_0^2/2$. So, the velocity after impact drops to $v_1 = v_0\sqrt{7/8} = 0.935\, v_0$.

By directly applying Korol and Sivakumaran's results [5] to WTC towers, the energy dissipation calculated by the plastic hinge mechanism [7, Sec.8.6] (according to the foregoing three assumptions) would have to increase by 3.5-times, i.e., $Mv_1^2/2 = (1 - \frac{7}{16})Mv_0^2/2$, which gives $v_1 = 0.750\, v_0$. Obviously, this updated estimate again indicates a continuing collapse. In no way the energy dissipation in the columns of one floor could be large enough to exceed $Mv_0^2/2$, which would be necessary to arrest the gravity-driven collapse.

After the crushing front advances by about ten floors, the collapsing mass grows significantly and the kinetic energy of the falling mass dwarfs the energy dissipated by the columns. It then ceases to matter whether or not the dissipation by plastic buckling is tripled. Therefore, the calculations of the overall duration of collapse, of the velocity of expelling air and debris shedding, and of the impact comminution of concrete slabs into particles, would not change beyond the range of error in the observations made.

Non-Rigid Restraints at Column Ends

The Korol and Sivakumaran's columns developed no plastic hinges at the ends. Their end supports had a flat free contact with the loading platens rather than perfect restraint. Beginning with a certain

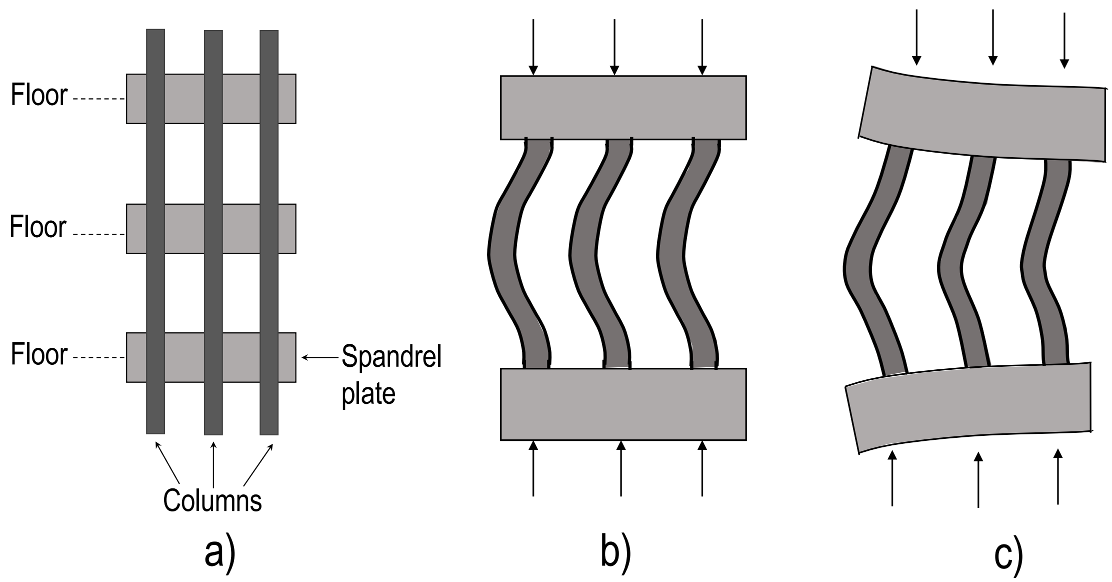

Figure 2: Deformation of the perimeter columns of WTC towers: a) geometry of the prefabricated unit of perimeter columns, b) deformation of columns with fully restrained ends, c) deformation of columns with elastically restrained ends.

small deflection without end rotations, the column ends pivoted freely about the end of one flange (Fig. 1). This complicates comparisons with the WTC columns.

The perimeter columns of the WTC towers were fabricated in units of three-story high. They consisted of three column sections and three spandrel plates (Fig. 2a). For each story, the rotation of the two ends of each column was restrained by the spandrel plates. The spandrel plates must have deformed elastically and plastically, rotating together with the column ends (Fig. 2c). Therefore the plastic hinges at the ends of WTC columns must have dissipated much less energy than the mid height hinge. This would make the estimate of energy dissipation per column much smaller than that calculated for a column with fixed ends (Fig. 2b).

Meanwhile, Korol and Sivakumaran's experiments indicated that, at the plastic hinge location, the columns experienced large plastic deformation on the tensile flange and local buckling on the compressive flange (Fig. 1). These local mechanisms make significant contributions to the total energy dissipation. However, for columns in the WTC towers, the two ends are not fully restrained and therefore the energy dissipation due to plastic deformation and local flange buckling at these two ends would be smaller than that at the mid-span. Therefore, we can conclude that, for columns in the WTC towers, the increase of the energy dissipation relative to the prediction by the plastic hinge model would be much smaller than that observed in Korol and Sivakumaran's experiments.

Limited Ductility and Fracture of Steel

To get a conservative estimate of the maximum possible dissipation, the ductility limitation and fracture of steel were neglected in previous studies [4, 3]. In reality, numerous column fractures were likely to occur, especially because a high rate of deformation promotes the fracture of steel. The fractures during WTC collapse, which greatly reduced energy dissipation, have been documented by photos and videos showing many flying fragments of columns.

The fracturing of columns must have been particularly intense in the columns of lower stories. They consisted of high strength steel (with the yield strength of 690 MPa), which is more brittle and much more prone to fracture, especially at high rate.

Calibration Based on Korol and Sivakumaran's Tests and Video Record of Collapse

The uncertainty in the estimation of the energy dissipation by column failures, by air and mass ejection and by comminution of concrete slabs, was recognized in the previous analysis of WTC collapse [2]. A sensitivity analysis was performed, in which plausible ranges of these dissipation terms were considered. For columns, a range of $\pm 20\%$ of the mean energy dissipation capacity was used (although, in view of Korol and Sivakumaran's tests, it should have been broader). For air and mass ejection, a range of $\pm 50\%$ of the mean energy dissipation capacity was considered.

The calculations showed that these variations make little difference in the predictions of the total collapse duration, as well as the crush front propagation and concrete slab comminution. A larger variation of the energy dissipation capacity of columns (i.e., more than 50% increase) was recognized to cause noticeable deviations from the video record of collapse during approximately the first two seconds (see Fig. 6 of [3]). Yet the match of the seismically recorded duration of collapse would barely be affected.

Based on the aforementioned discussion, the increase of energy dissipation in columns indicated by Korol and Sivakumaran's test data does not make an appreciable difference in the failure analysis of progressive failure of WTC columns. It makes an appreciable difference only for matching the video record of the first two seconds of collapse. Therefore, the proper way of using these data together with this video record is to exploit them for calibrating the energy dissipation per column, restricted, of course, to the realistic range of uncertainties in the material and structure properties.

A calibration of this kind has already been done in the previous study [2], which showed that, for the upper stories, the energy dissipation capacity of columns was about 2/3 of the value predicted by the simple plastic three-hinge model with perfectly rigid end constraints. The 2/3 reduction is not unreasonable if we consider the decrease in energy dissipation due to the flexible end restraints, material fracture, and possible multi-story buckling [2]. This decrease can greatly offset the increase of the energy dissipation due to local plastic deformation and local buckling at the hinges. Anyway, note that by using the calibrated energy dissipation capacity of columns, the model was able to predict correctly all the other observations such as the seismically documented collapse duration, the particle size distribution of fragmented concrete slabs; the wide spread of the fine dust around the tower; the loud booms heard during the collapse; and the fast expansion of dust clouds during collapse. This multitude of data matching serves as a strong validation of the overall model.

Conclusion

The experiments of Korol and Sivakumaran help in clarifying the mechanics of energy dissipation in the columns of WTC and in reducing the previously stated range of uncertainties of analysis. They indicate that if the column ends were rigidly supported and if the ductility of steel was unlimited, then the simple plastic three-hinge mechanism with constant bending moments [7, Sec.8.2], of the type used for small-deflection buckling, would have dissipated about 3.5-times as much energy than considered in previous studies.

But calibration by matching of the video record of initial collapse implies that this energy must have been reduced to about 2/3 of the energy predicted by the three-hinge model. This estimated 2/3 reduction must have been caused by the fracturing of steel and by the flexibility of spandrel beams which reduced the rotations of the plastic hinges at column ends. With this update of input data, all the observed features of the WTC collapse remain to be closely matched by the gravity-driven mechanics of progressive collapse.

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