increasingly influenced the deterministic physics-based collapse process, and the details of the progression of the horizontal failure and final global collapse were increasingly less precise.

Thus, while the two predictions of the time of descent of the west penthouse also straddled the observed time, the mechanisms of building decay were quite different. In the analysis without debris impact damage, the exterior columns buckled near mid-height of the building, approximately between Floors 17 and 29. In the analysis with debris impact damage, the exterior columns buckled between Floors 7 to 14, due to the influence of the exterior damage near the southwest corner. In both analyses, the eastern exterior wall deflected inward at the roof level as the structure became unsupported after the vertical collapse event. The western wall also deflected inward in the analysis without debris impact damage, as it was pulled inward as the last line of core columns failed.

There was another observable feature that occurred after the global collapse was underway and, thus, could not be captured accurately in the simulation. After the exterior facade began to fall downward at 6.9 s, the north face developed a line or "kink" near the end of the core at Column 76. As shown in Figure 5-205, the northeast corner began to displace to the north at about 8.8 s, and the kink was visible at 9.3 s. The kink and rotation of the northeast façade occurred 2 s to 3 s after the exterior façade had begun to move downward, as a result of the global collapse.

Given the complexity of the modeled behavior, the global collapse analyses matched the observed behavior reasonably well. The global collapse analyses confirmed the leading collapse hypothesis, which was based on the available evidence.

12.5.3 Timing of Collapse Initiation and Progression

The timing of global collapse of WTC 7, as indicated by downward motion of the north wall, was investigated using a video of the collapse taken from the vantage point of West Street near Harrison Street (Camera No. 3, Figure 5-183). The pertinent building dimensions were determined using architectural drawings (Roth 1985). An initial analysis compared the observed time for the roofline to fall approximately 18 stories to the free fall time under the force of gravity. A more detailed analysis examined the vertical displacement, velocity, and acceleration through different stages of the collapse process.

The initial analysis required two quantities: (1) the distance that some feature of the building descended and (2) the time it took to fall that distance. The chosen feature was the top of the parapet wall on the roofline aligned with the east edge of the louvers on the north face. The distance was the difference between the elevation of the roofline prior to the collapse and the last elevation where the roofline could be observed before it was obstructed by a building in the foreground.

The elevation of the top of the parapet wall was +925 ft 4 in. The lowest point on the north face of WTC 7 that was visible on the Camera 3 video, prior to any downward movement, was the tops of the windows on Floor 29, which had an approximate elevation of +683 ft 6 in. Thus, the distance that the roofline moved downward before it disappeared from view was about 242 ft.

It was difficult to detect the exact instant that the north wall began to collapse because of the resolution of the video image and because, as columns buckled, vertical movement was initially very small. The instant of initial movement was estimated by analyzing changes in the color of a pixel in the video recording over time. A single pixel close to the center of the north face roofline was selected and the color of the pixel, expressed as values of hue, saturation, and brightness, was recorded for each frame between 6.0 s and 7.8 s, where $t = 0$ s corresponds to the start of descent of the east penthouse (see Table 5-3). The brightness was found to provide the best indicator of change since the brightness of a pixel representing the sky above the building had a value of 100 percent while a pixel representing the roofline of the building (granite façade) had a brightness of roughly 60 percent for the pixel selected. The brightness of the selected pixel, expressed as a percent, is plotted versus time in Figure 12–75. From 6.0 s to 6.9 s, the brightness is seen to oscillate around a value of 60 percent indicating no vertical movement. Beginning at roughly 6.9 s the brightness increases irreversibly to a value of 100 percent at which time the pixel under study represents the sky. Thus, the relative time at which the roofline began to move was estimated as 6.9 s. The time when the roofline dropped from view behind the buildings in the foreground was 12.3 s. Thus, the time the roofline took to fall 18 stories was approximately 5.4 s.

The theoretical time for free fall (i.e., at gravitational acceleration) was computed from,

$$t = \sqrt{\frac{2h}{g}} \quad (1)$$

where t = time (s), h = distance (ft), and g = gravitational acceleration (32.2 ft/s^2). Upon substitution of $h = 242$ ft in the above equation, the estimated free fall time for the roofline to descend 18 stories was approximately 3.9 s. Thus, the average time for the upper 18 stories to collapse, based on video evidence, was approximately 40 percent longer than the computed free fall time.

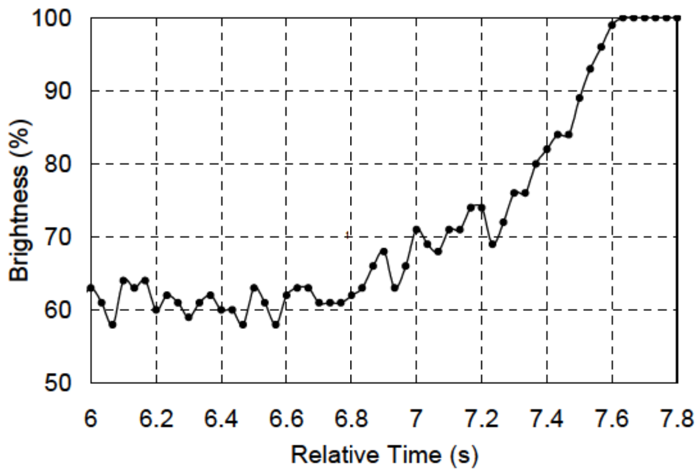

Figure 12–75 Brightness of a pixel on the north face roofline as WTC 7 began to collapse.

To obtain a better understanding of the vertical motion of the building in the first several seconds of descent, the motion of the north face was studied in more detail by tracking the vertical position of a point near the center of the roofline using the same video. In the following discussion, the time at which motion of the roofline was first perceived (6.9 s) is taken as time zero.

Figure 12–76 presents a plot of the downward displacement data shown as solid circles. A curve fit is also plotted with these data as a solid line. A function of the form $z(t) = A\{1 - \exp[-(t/\lambda)^k]\}$ was selected because it is flexible and well-behaved, and because it satisfies the initial conditions of zero displacement, zero velocity, and zero acceleration. The constants A, λ, and k were determined using least squares fitting. The fitted displacement function was differentiated to estimate the downward velocity as a function of time, shown as a solid curve in Figure 12–77. Velocity data points (solid circles) were also determined from the displacement data using a central difference approximation[1]. The slope of the velocity curve is approximately constant between about 1.75 s and 4.0 s. To estimate the downward acceleration[2] during this stage, a straight line was fit to the open-circled velocity data points using linear regression (shown as a straight line in Figure 12–77). The slope of the straight line, which represents a constant acceleration, was found to be 32.2 ft/s^2 (with a coefficient of regression $R^2 = 0.991$), equivalent to the acceleration of gravity g. Note that this line closely matches the velocity curve between about 1.75 s and 4.0 s.

For discussion purposes, three stages were defined, as denoted in Figure 12–77:

- In Stage 1, the descent was slow and the acceleration was less than that of gravity. This stage corresponds to the initial buckling of the exterior columns in the lower stories of the north face, as seen in Figure 12–62. By 1.75 s, the north face had descended approximately 7 ft.
- In Stage 2, the north face descended at gravitational acceleration, as exterior column buckling progressed and the columns provided negligible support to the upper portion of the north face. This free fall drop continued for approximately 8 stories (105 ft), the distance traveled between times $t = 1.75$ s and $t = 4.0$ s.
- In Stage 3, the acceleration decreased somewhat as the upper portion of the north face encountered resistance from the collapsed structure and the debris pile below. Between 4.0 s and 5.4 s, the northwest corner fell an additional 130 ft.

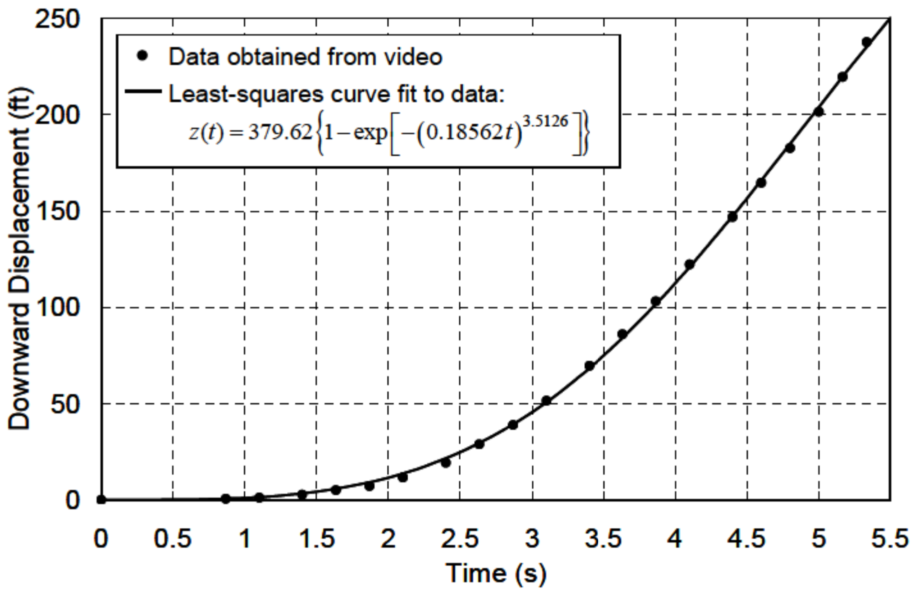

Figure 12–76 Downward displacement of north face roofline as WTC 7 began to collapse.

[1] The central difference approximation is given by $v_{i+½} \approx (z_i - z_{i+1})/(t_i - t_{i+1})$, where z_i and z_{i+1} denote the displacement at time t_i and t_{i+1}, respectively

[2] Acceleration, or rate of change of velocity, is equal to the slope of a velocity versus time curve.

As noted above, the collapse time was approximately 40 percent longer than that of free fall for the first 18 stories of descent. The detailed analysis shows that this increase in time is due primarily to Stage 1, in which column buckling was just beginning and gradual increases in displacement and velocity were observed. The three stages of collapse progression described above are consistent with the results of the global collapse analyses discussed earlier in this chapter.

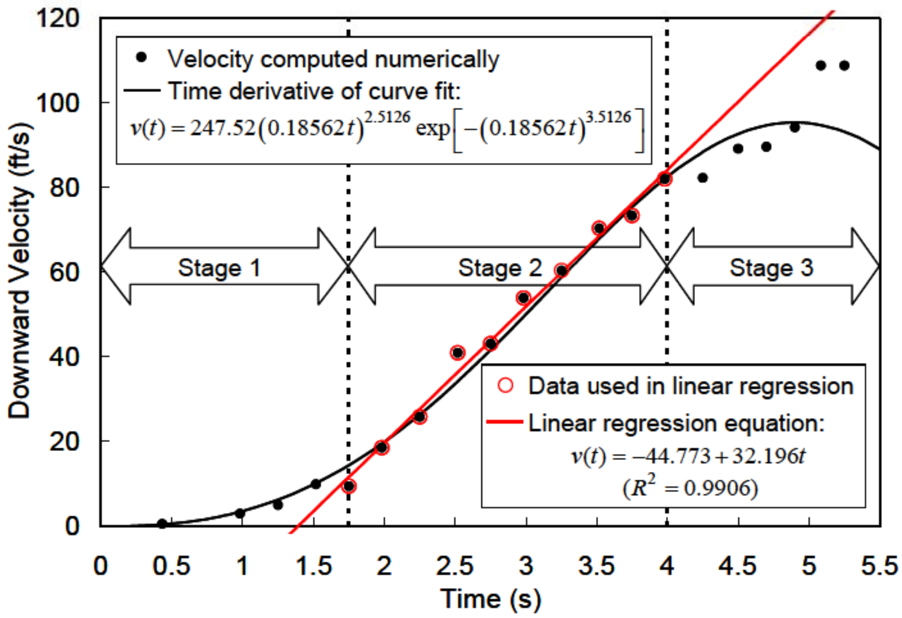

Figure 12–77 Downward velocity of north face roofline as WTC 7 began to collapse.

12.6 SUMMARY OF FINDINGS

A global finite element model of WTC 7 was developed using LS-DYNA to calculate the structural response of WTC 7 to a fire-induced initial failure event and to determine the sequence and timing of the events that led to the global collapse of the building. Four simulations were performed with this model.

- The first was based on NIST's best estimate of both the debris impact damage from WTC 1 and the fire-induced damage, from the ANSYS analysis. This occurred at 4 h in the ANSYS computation.
- The second simulation differed only in the input of a lesser degree of fire-induced damage at 3.5 h in the ANSYS computation. The purpose of this simulation was to determine whether a lesser degree of fire-induced damage could lead to the collapse of WTC 7.
- The third simulation was the same as the first, except that no debris impact damage was included. The purpose of this analysis was to determine the contribution of debris impact to the WTC 7 global collapse sequence and whether WTC 7 would have collapsed solely due to the effects of the fires.
- In the fourth simulation, the building experienced no debris or fire-induced damage. A section of Column 79 between Floors 11 and 13 was removed. The purpose of this analysis