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An Engineering Perspective of the Collapse of WTC-I

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Abstract: We report on a simulation study of the performance of the North Tower (WTC-I) of the World Trade Center complex during the impact of American Airline Flight 11, on September 11, 2001. We discuss impact damage the structural core might have sustained and its possible behavior under structural and thermal loading. Our simulations indicate that the worst damage to the core structure was in stories 95 through 97 of the tower. We estimate that a core collapse mechanism could be initiated if the tower core column temperatures were elevated to about 700^{o}C.

CE Database subject headings: Collapse; Computer-aided simulation; Impact loads; Models; Structural analysis; Structural engineering; Structural failure; Thermal analysis.

Introduction

We report our perspective of the failure mechanism of the North Tower of the World Trade Center (WTC-I) on 11 September 2001 resulting from the impact of Flight AA11. Our

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conclusions are drawn from the results of a series of detailed numerical analyses of the impact, using finite-element modeling.

That the World Trade Center Towers withstood the impact loads of commercial aircrafts on September 11, 2001, was not surprising for structural engineers. However, very few in the profession expected the collapse of the towers during the fires that followed. Since then, several studies including impact and fire simulations have been conducted to estimate the sequence of events leading to collapses and to understand the overall performance of the towers under impact and thermal loads (e.g. FEMA 2002, NIST 2005, Bažant and Zhou 2002, Wierzbicki and Teng 2002, Omika et al. 2005, Karim and Fatt 2005). This paper describes the damage indicated by the simulations and analyses made at Purdue University, and provides an engineering perspective of the event.

No detailed observational data on the performance of tower core elements exist. Therefore, the Purdue research team used finite element simulations to assist in estimating the impact response and the post-impact state of the structural elements in the core. Objective evaluations of the simulation results indicated that identification of the number and distribution of columns damaged immediately by the impact was quite sensitive to the input parameters. As would be expected, the simulations did indicate consistently some damage to the core columns but credible changes in input parameters such as flight or column properties resulted in changes in calculated impact damage suggesting that an exact determination of the damage to the core was not defensible. On the other hand, it was found that a simple construct, not dependent on exact identification of the damage distribution, would explain the collapse.

The study concentrated on the core structure of the tower and its possible behavior under impact and thermal loads. It was not the purpose of the study to rule out other plausible mechanisms initiating collapse of the WTC-I tower, such as one due to loss of lateral bracing and buckling of perimeter columns induced by failure of open-web floor joists under thermal loads, or other failure mechanisms. Rather, the object of the paper is to show that a simple and credible hypothesis will suffice to explain the observed collapse.

The Purdue study included development of detailed finite element models of the Boeing 767-200ER aircraft and the top twenty stories of the World Trade Center I (WTC-I). Simulations were made using the LS-DYNA (LSTC 2005) to investigate the performance of the core structural elements during the impact. Aircraft fuel was modeled using smoothed particle hydrodynamics (SPH) elements to simulate fluid-structure interaction during the impact. Only the incombustible behavior of the fuel particles was considered. The fire that followed the impact was not simulated.

Modeling of the Boeing 767-200ER Aircraft

A detailed FEA model of the Boeing 767-200ER aircraft was developed based on data available from public sources (Badrocke and Gunston 1998, Boeing CAG). Information gathered from documents on similar aircraft was used for aircraft parts for which no material or dimensional information was available. Figure 1 shows the overall dimensions of the aircraft.

Aircraft dry mass of 98 tonnes, as given in the National Institute of Standard and Technology report (NIST 2005), was matched in the numerical model. Approximately 110,000 elements were used to model the solid parts of the aircraft. The fuel, totaling 30 tonnes in mass, was modeled using approximately 90,000 smoothed particle hydrodynamics (SPH) elements. Aluminum and titanium are the material of choice for most of the aircraft components. In our computer model, an aluminum material model with yield strength of 380 MPa (55 ksi) and limiting true strain of 10% was used. For titanium elements, a titanium material model with yield strength of 860 MPa (125 ksi) and limiting true strain of 10% was used. No strain-rate effects were included in any of the material models.

Figure 2 shows the mass distribution for the solid parts and fuel along the length of the aircraft model.

Modeling of the World Trade Center Tower I

The top twenty stories of the WTC-I, stories 89 through 110, were modeled numerically for use in impact simulations. Data from public sources were used to set the dimensions of the structural elements. The self-weight of the 10 cm (4-inch) thick light-weight concrete floor slabs was increased to 3.1 kPa (65 psf) to account for the superimposed dead load and live load on the floors. Approximately 125,000 elements were used to develop the numerical model. Figure 3 shows an isometric view of the developed WTC-I model.

For steel elements, that constitute all the structural elements except for the floor slabs, steel material models with appropriate yield strengths in the range of 290-690 MPa (42-100 ksi) and limiting true strain of 40% were used. For lightweight concrete slabs, concrete material model with strength of 28 MPa (4 ksi) and limiting true strain of 0.5% was used. No strain-rate effects were included in any of the material models.

Impact Simulation

The aircraft and tower models were used to simulate and analyze the response of the tower structure to the impact of the aircraft. The initial conditions for the aircraft impact were set as follows: flight-speed of 450 mph (200 m/sec), roll angle of 25^o (left wing down); pitch angle of 10^o (downward from horizontal), and yaw angle of 0^o. An elevation of the north face of the WTC-I with the aircraft at the instant of impact is shown in Figure 4.

Computational Issues

Impact simulations were performed using the nonlinear finite-element-based dynamic analysis software LS-DYNA [version 970 r5434a SMP] (LSTC 2005) on the IBM multi-processor nano-regatta computer system at Purdue University. Typically, we simulated the first 0.5 second of the time after impact and used adaptive incremental approach resulting in an average of 1.0×10^{-6} sec time-steps.

Damage to WTC-I exterior structural elements

Figure 5 shows the damage to the external structure of the tower caused by the penetrating aircraft. The top figure shows the damage indicated by the simulation. The bottom illustration in Figure 5 shows the actual damage observed on 11 September 2001. The profile of the aircraft is clearly visible in the damage to the exterior structural elements. Similar to what happened during the actual event, tips of the aircraft wings were calculated to cause negligible or no damage to the perimeter structure of the WTC-I tower in the computer simulation.

Damage to WTC-I core structural elements

There were forty-seven columns arranged in six column lines in the core structure of WTC-I. Figure 6 shows the core columns as well as the perimeter columns on a typical floor plan. Figure 7 shows a perspective view of the columns and floor slab of the 95th story.

Because there is no observational information on the state of core structure after the aircraft impact, computer simulations are used to estimate the damage sustained by the structural elements in WTC-I core.

Table 1 lists the estimated number of heavily damaged core columns according to our final simulation. However, it must be added that during the series of simulations performed, we found the estimates to be very sensitive to model parameters such as failure strain of materials, to the extent that in the heavily damaged stories 95 through 97, the number of damaged columns could be as few as half the numbers listed in Table 1. This observation was not surprising given the fact that simulation results reported by other researchers (see for example, NIST 2005 and Omika et al. 2005) with regards to damage to the core columns are scattered over a wide range. Table 2 lists the estimates for maximum number of destroyed core columns as reported by various research groups.

From the results obtained at Purdue and elsewhere, it is evident that to determine by calculation the exact number of columns damaged by the impact is beyond the technology currently available to us. However, in our simulations, we observed that the heavy damage to the core columns concentrated consistently at stories 95 through 97. This too should not be considered surprising given the fact that the aircraft impacted the WTC-I tower at or very close to floor level 96 and that the airplane had the greatest concentration of mass close to its centerline.

Figure 8 shows the core columns in story 95 estimated to be heavily damaged or destroyed by direct aircraft impact or airborne debris. Several beams in the region with heavy column damage were estimated to be destroyed. However, in our simulations, no standing column was found to have lost all of the beams attached to it. Core columns in story 95 were studied further to estimate their behavior under thermal loads that ensued after the aircraft impact.

Simplified Capacity Analysis for the Core

There were six lines of columns in the core (Figure 7). Five of them had eight columns each, while the remaining column-line had seven columns, giving a total of forty-seven columns. Columns along the north and south edges of the core supported floor spans of 65-ft. Relative to other core columns, these columns had larger cross sections. In fact, it is estimated that each of the north and south column lines provided approximately 30% of the total vertical load carrying capacity of the core. It is estimated that each of the remaining four core column lines provided approximately 10% of the total capacity of the core.

Thermal Behavior Study of Core Columns

Estimates of axial load capacity of core columns in story 95 under various thermal load levels were made to study the behavior of these columns under elevated temperatures. Eurocode 3 (ECFS 2005) is used to estimate the changes in modulus of elasticity and yield strength of steel with temperature, and to provide an axial load capacity estimate for core columns. Figure 9 illustrates the reduction in modulus of elasticity and effective yield strength of carbon steel with temperature as estimated by Eurocode 3 (ECFS 2005).

In the analysis, unbraced lengths of columns were taken to be equal to story height, i.e. 3.6 m (12 feet), with pin (moment-free) boundary conditions at both ends. Only axial loading was considered in the analysis.

Figure 10 shows the calculated relationship between axial load capacity and temperature for a representative core column.

As seen in Figure 10, reductions in axial load capacities of core columns are minimal up to column temperatures of 400^{o}C. At higher temperatures, the strength of the columns reduces significantly with increase in temperature. By about 550^{o}C, the column axial load capacity is reduced to 1/2 of the capacity at 20^{o}C. At about 700^{o}C, the capacities are reduced to 1/5 and at 800^{o}C columns to 1/10 of their normal operation capacities. For all core columns, inelastic buckling was found to be the critical failure mechanism.

Figure 11 shows the estimated temperature dependency of the cumulative axial load capacity of the core columns at the 95th story. Two of the cases for the state of the core structure are illustrated: full set of core columns (no damage); damaged core case (simulation estimate) in which the total axial load capacity is reduced by 1/4. An estimated gravity load (demand) of 75x10^{6} N due to dead load and live load is also shown in Figure 11.

The demand and full-core capacity curves in Figure 11 suggest that if 95th story core columns had free heights of 3.6 m, i.e. if they were restrained at the top and bottom of the story, when the core reached approximately 700^{o}C, the structure would not be able to sustain the axial loads from the stories above and a core collapse would be initiated.

When damage to the core columns in story 95 is taken into consideration, the limit state is reached at a lower temperature (see Figure 11). The reduction in the level of critical temperature is estimated to be no more than 50^{o}C. In other words, even though the aircraft impact loads may have eliminated a significant number of core columns, the damage to core structure had, ultimately, little effect on the critical thermal load level to fail the core under axial gravity loads.

Although not illustrated in here, if the core columns were to lose their lateral supports and their free heights became more than 3.6 meter, even though there would be significant reduction in the total axial load capacity of the core columns, the estimated ultimate failure temperature would not have changed that significantly. For example, doubling the free-height to two-stories reduces the total axial capacity by about 30-40% but reduces the failure temperature to only about 600^{o}C or about 650^{o}C if no damage to core columns were considered. Again the damage to core columns from impact loads could be considered immaterial when viewed from ultimate thermal load capacity of the core structure. In thermal load analysis for response of structural elements at high temperatures under actual conditions, the effect of a 50^{o}C difference in temperature is hardly distinguishable, given all the uncertainties.

It is evident from observation and our simulations that the debris of the aircraft went through the WTC structure at stories 94 through 97. Much of the fire insulation would have been scoured off leaving the steel elements unprotected during the immediately following fire event. Experimental data for steel in that condition (Buchanan 2000) indicate that the metal temperature in all unprotected structural elements would have reached 700 ^{o}C in a typical office fire. That condition would suffice to initiate instability (e.g. Ali and O’Connor 2001, Wang and Davies 2003) even if all the girders were intact and the failure mechanism was limited to one story of the core structure.

Conclusions

Impact simulations indicate that the damage states of the WTC-I core structural elements are very sensitive to analysis parameters and as such, it is not possible to suggest the exact state of the core framing after the aircraft impact. Simulations indicate consistently that the worst damage to the core structure was sustained in the 95th through 97th stories of the tower.

For both the intact and plausible compromised core states considered, it is estimated that a core collapse mechanism could have been initiated in WTC-I if the tower core column temperatures were elevated to approximately 700^{o}C. As the aircraft debris went through several stories in the tower, much of the thermal insulation on the core columns would have been scoured off. Under such conditions, the ensuing fire would be sufficient to cause instability and initiate collapse. From an engineering perspective, impact damage to the core structure had a negligible effect on the critical thermal load required to initiate collapse in the core structure.

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References

Ali F. and O'Connor D. (2003) "Structural performance of rotationally restrained steel column in fire" *Fire Safety J.*, 36, 679-691.

Badrocke M. and Gunston B. (1998). *Boeing Aircraft Cutaways*. Osprey Publishing Ltd., Oxford, Great Britain.

Bažant Z.P. and Zhou Y. (2002). "Why did the World Trade Center collapse?" *J. Engineering Mechanics*, 128(1), 2-6.

Boeing Commercial Airplane Group. (undated). *747 Structures*, Seattle, Washington.

Buchanan A. H. (2001). *Structural Design for Fire Safety*. John Wiley and Sons, Ltd., West Sussex, England.

European Committee for Standardization. (2005). *EN 1993-1-2: Eurocode 3 - Design of Steel Structures – Part 1-2: General rules – Structural fire design.* Brussels, Belgium.

Federal Emergency Management Agency (FEMA). (2002). *World Trade Center Performance Study: Data Collection, Preliminary Observations, and Recommendations*. FEMA 403, Washington, DC.

Karim, M.R. and Fatt M.S.H. (2005). "Impact of the Boeing 767 aircraft into the World Trade Center." *J. Engineering Mechanics*, 131(10), 1066-1072

Livermore Software Technology Corp. (LSTC). (2005). *LS-DYNA v970 r5434a SMP version*. Livermore, CA.

National Institute of Standards and Technology (NIST). (2005). *Final Report of the National Construction Safety Team on the Collapses of the World Trade Center Towers*. *NIST NCSTAR 1*, Gaithersburg, MD.

Omika Y., Fukuzawa E., Koshika N., Morikawa H., and Fukuda R. (2005). "Structural responses of World Trade Center under aircraft attacks." *J. Structural Engineering*, 131(1), 6-15.

Wang Y.C. and Davies J.M. (2003). "An experimental study of non-sway loaded and rotationally restrained steel column assemblies under fire conditions: analysis of test results and design calculations." *J. Constructional Steel Research*, 59, 291-313.

Wierzbicki T. and Teng X. (2003). "How the airplane wing cut through the exterior columns of the World Trade Center." *Int. J. Impact Engineering*, 28, 601-625.

Table 1. Number of core columns estimated to be destroyed or heavily damaged during the aircraft impact.

Location	No of damaged columns
Story 99	1
Story 98	1
Story 97	16
Story 96	14
Story 95	17
Story 94	3

Table 2. Damage to WTC-I core columns reported by other investigators. Data are from Omika et al. 2005 (*) and NIST 2005 (**). Table adapted from NIST 2005.

Analysis	**Total number of damaged core columns and, if indicated, story with highest number of core columns damaged**
(*) Kajima Corp.	
• Impact Analysis	18 collapsed + 3 fractured; story 95
(**) MIT	
• Impact Analysis	4-12 failed
(**) NIST	
• Less Severe Impact Analysis	1 severed + 2 heavily damaged; story 96
• Base Case Impact Analysis	3 severed + 4 heavily damaged; story 94
• More Severe Impact Analysis	6 severed + 3 heavily damaged; story 95
(**) Weidlinger Associates Inc.	
• Impact Analysis	23 failed/heavily damaged
• Collapse Analysis	20 failed

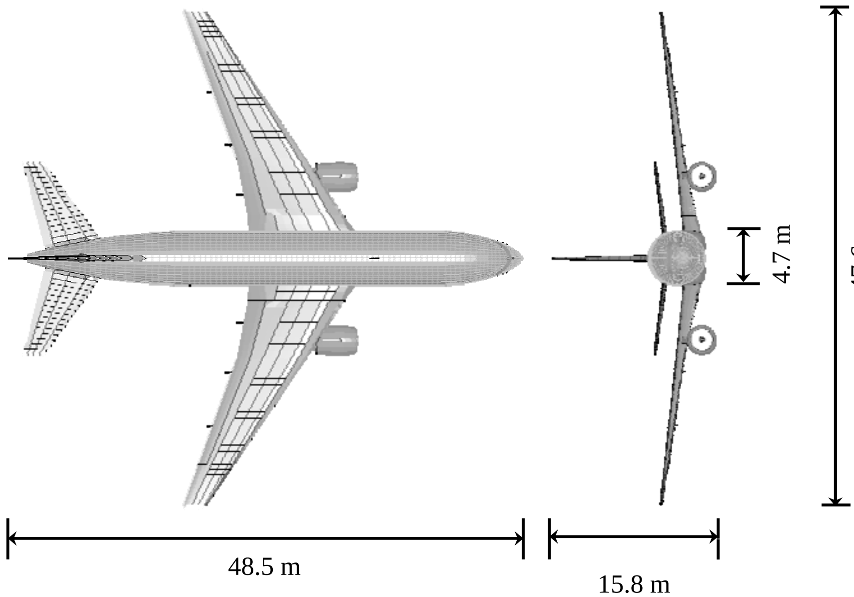

Figure 1. Overall dimensions of Boeing 767-200ER.

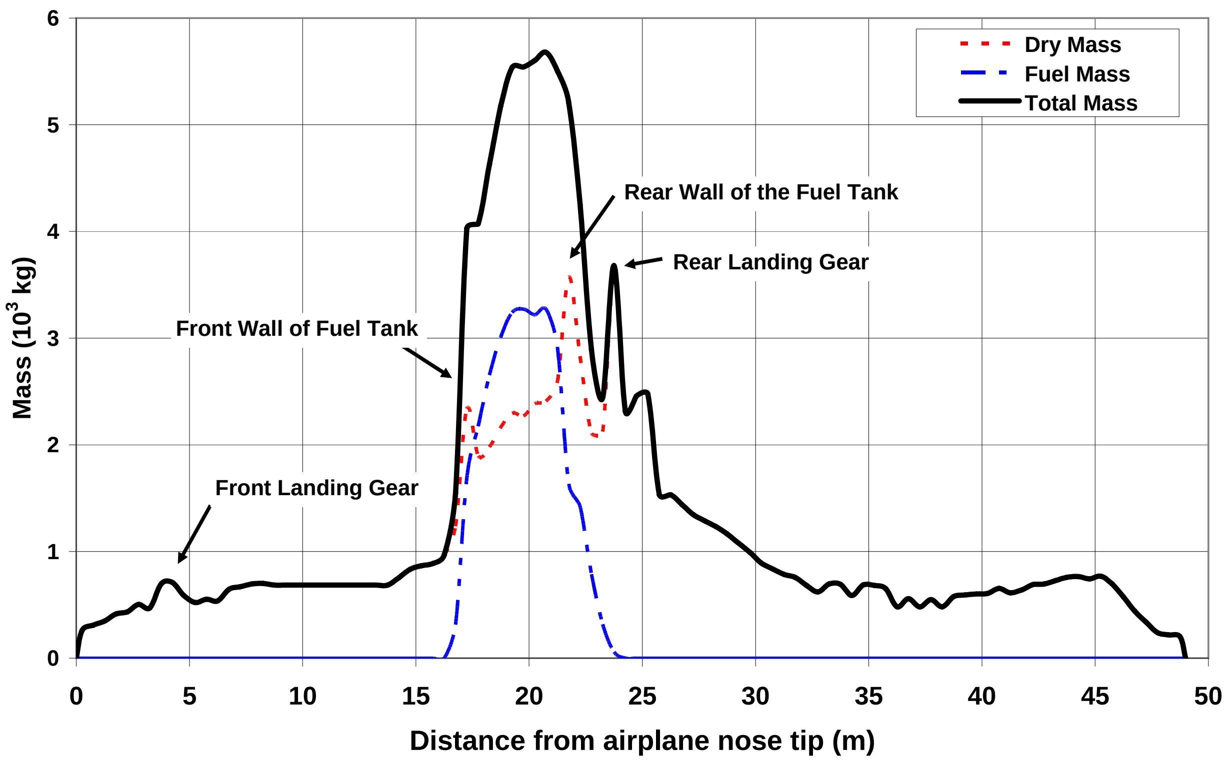

Figure 2. Distribution of the solid, fuel, and total mass along the length of the Boeing 767-200ER model.

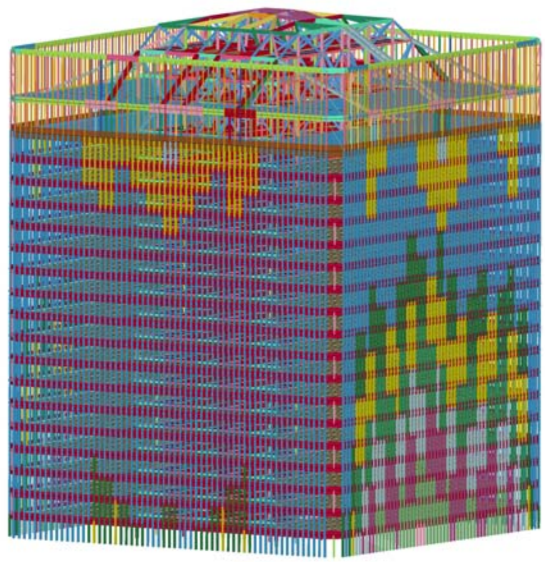

Figure 3. Elevation of the WTC-I model.

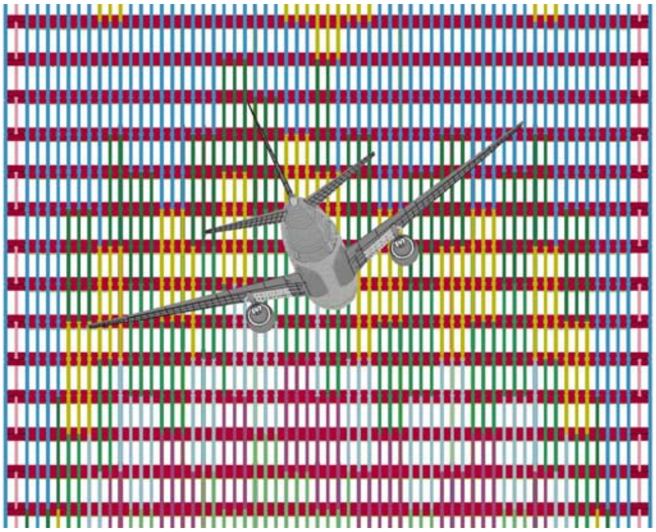

Figure 4. Elevation showing the aircraft impacting the north face of the tower.

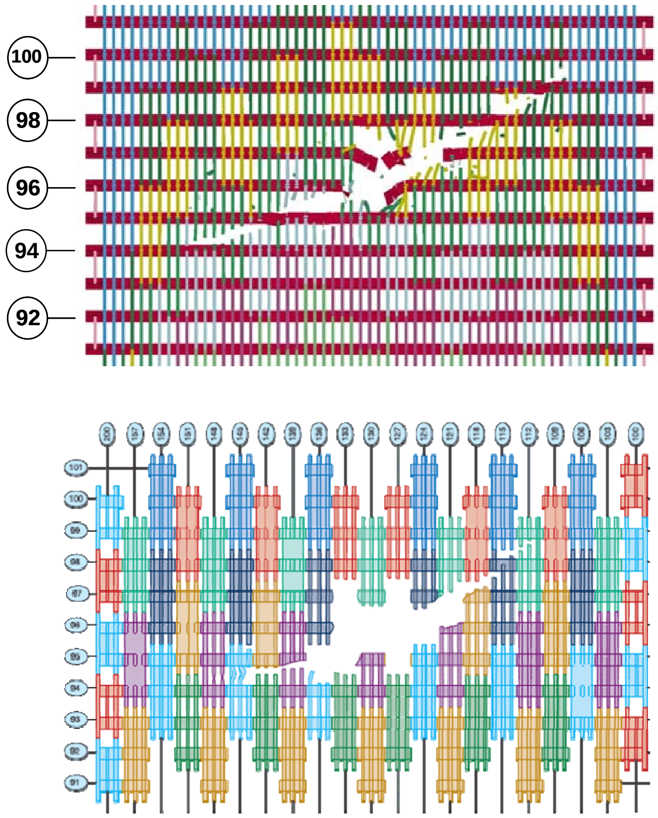

Figure 5. Damage to the tower skin structure estimated from the computer simulation (top) and observed on 11 September 2001 (bottom; source: FEMA 2002).

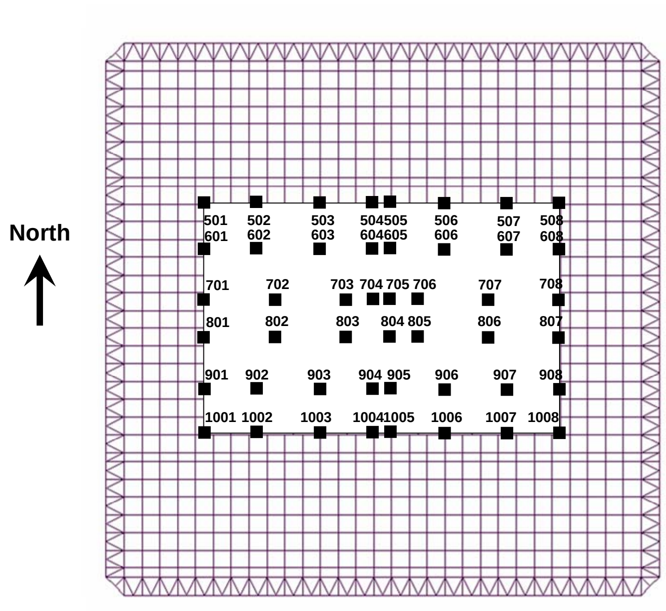

Figure 6. Floor plan of WTC-I showing 47 interior (core) columns and 240 exterior (perimeter/skin) columns.

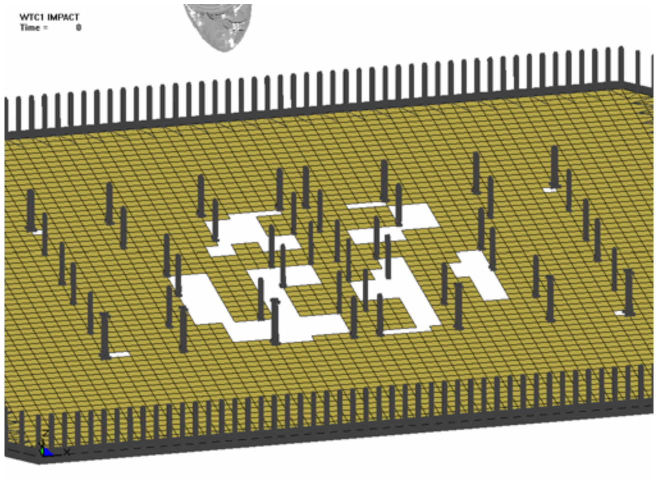

Figure 7. Story 95 cut-out showing the core columns, floor slab, and perimeter columns along the south and north faces of WTC-I. Incoming aircraft can be seen on the north side.

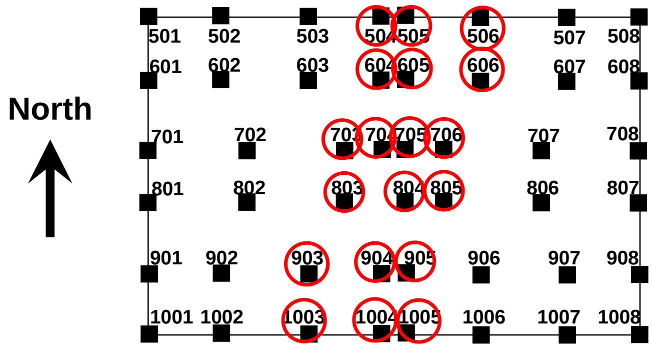

Figure 8. Core columns estimated to be heavily damaged or destroyed in numerical simulation.

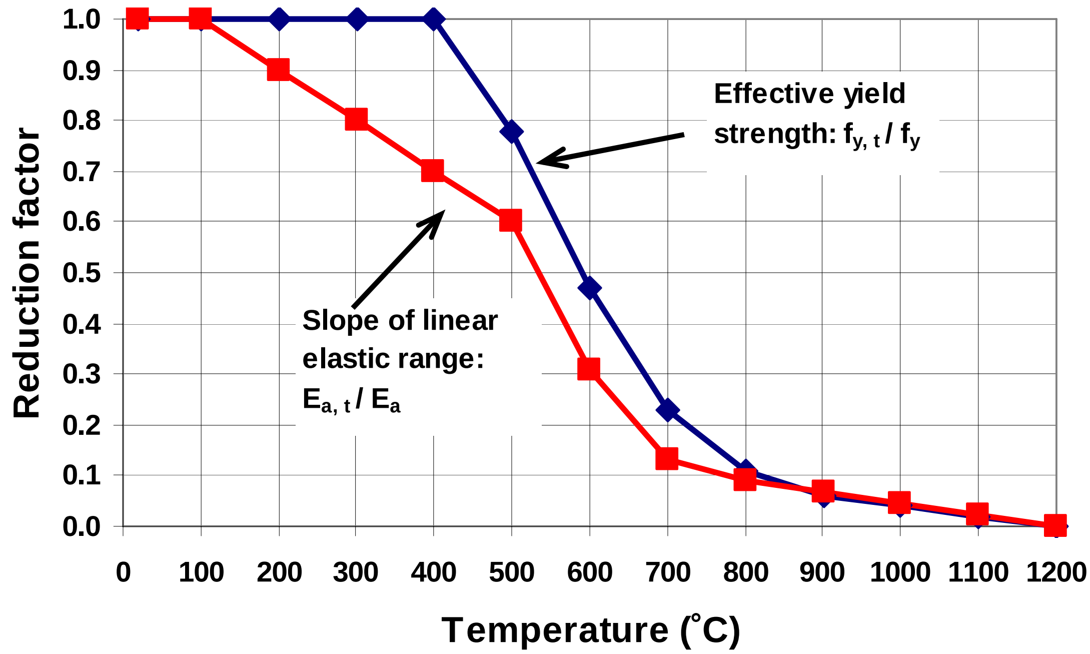

Figure 9. Reduction factor for effective yield strength given as ratio of yield strength $f_{y,t}$ at temperature t to yield strength f_y at 20°C, and reduction factor for modulus elasticity given as ratio of slope $E_{a,t}$ of linear elastic range at temperature t, and to slope E_a of linear elastic range at 20°C, per Eurocode 3 (ECFS 2005).

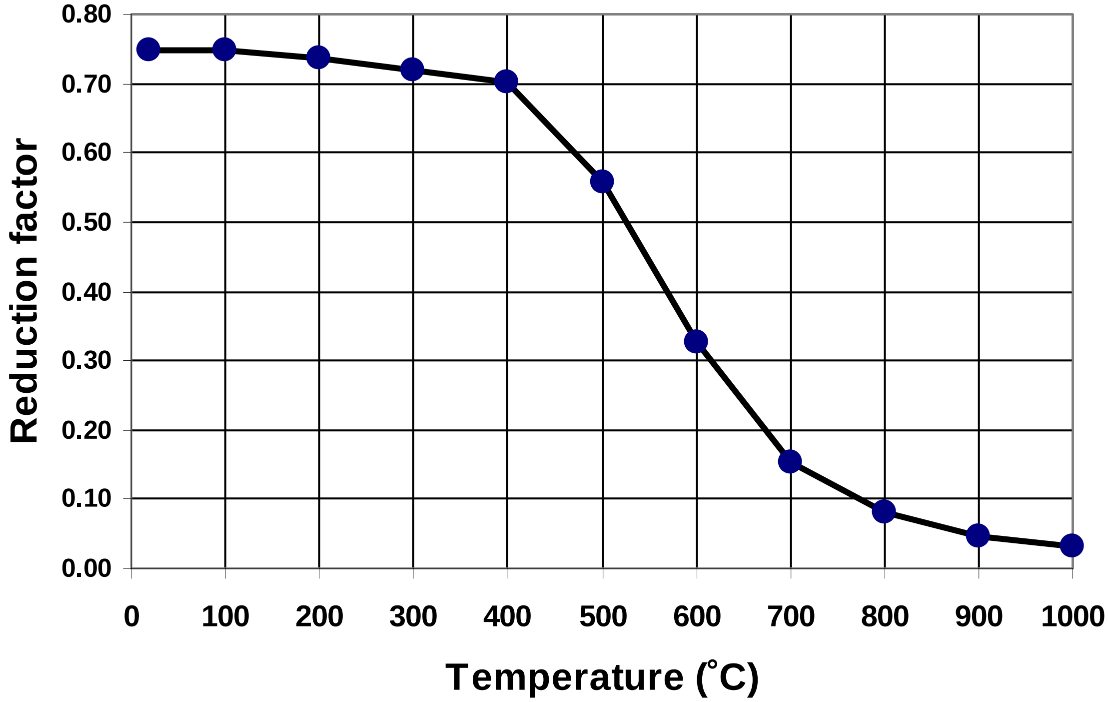

Figure 10. Ratio of column axial load capacity (buckling) at a given steel temperature to yield load at 20°C, for a representative core column.

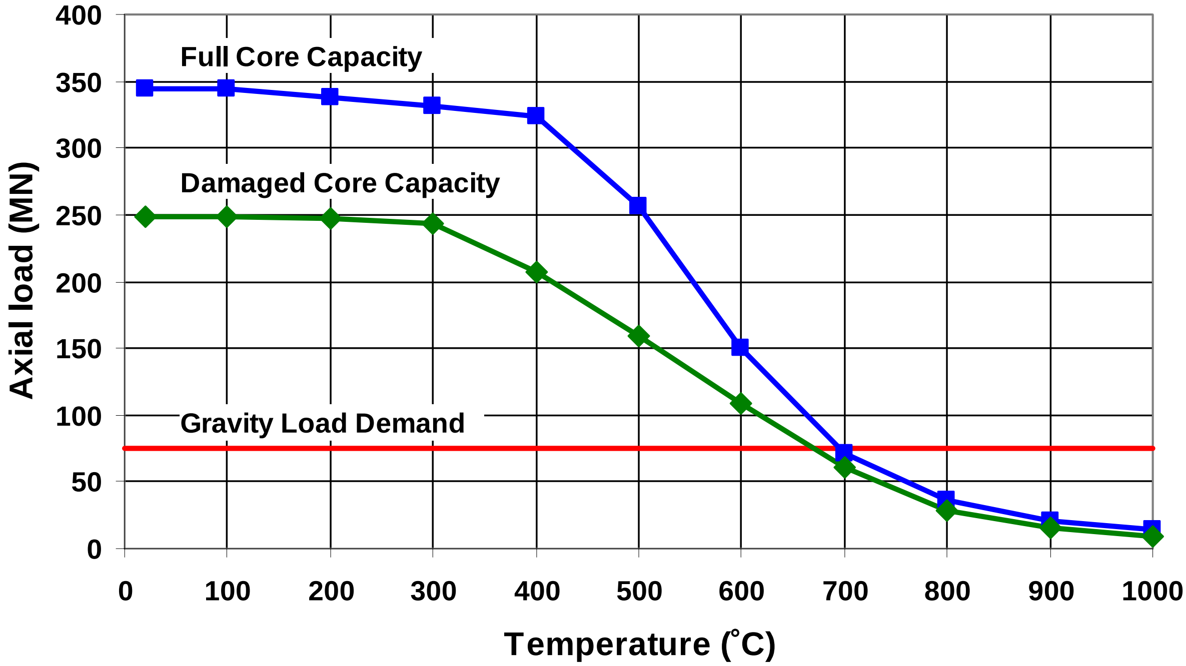

Figure 11. Axial load capacity of core columns and estimated gravity load demand at story 95 of WTC-I.