Accepted Manuscript -- Not Copyedited
Fire Technology, August 11, 2012, DOI: 10.1007/s10694-012-0286-5

Structural Analysis of Impact Damage to World Trade Center Buildings 1, 2, and 7*

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Abstract. The National Institute of Standards and Technology (NIST) conducted an extensive investigation of the collapse of World Trade Center towers (WTC 1 and WTC 2) and the WTC 7 building. This paper describes the reconstruction of impact damage to each of the WTC buildings, as well as analytical studies related to the WTC building collapses. In addition, data and evidence that were collected, tests of the floor truss systems in the WTC towers that were conducted, the overall structural analysis approach, and the development of the collapse hypotheses are discussed to provide a basis for the impact analyses and the fire and structural response analyses in a companion paper. Three companion papers address the primary structural systems of the WTC towers and WTC 7, the effects of fire on the three buildings, and how these events contributed to building collapse. The papers provide an overview of the complex and extensive investigations undertaken by NIST at a level of detail that has scientific merit but presents key aspects from the voluminous official reports at a level suitable for the technical literature.

The aircraft impact damage to structural members and their passive fire protection in WTC 1 and 2 were estimated through detailed aircraft impact simulations. The impact damage to WTC 7 was estimated from photographs after the collapse of WTC 1, where falling debris damaged the southwest corner of WTC 7. Based on the aircraft impact simulation, over half of the exterior columns on the north face of WTC 1 were severed and approximately 20 percent of the core columns were severed or heavily damaged. Spray-applied fire resistive material (SFRM) was dislodged by direct debris impact over five floors (Floors 94 to 98). WTC 2 structural damage was concentrated on the east side of the building. Over half of the exterior columns on the south face were severed and approximately 25 percent of the core columns were severed or heavily damaged. SFRM was dislodged by direct debris impact over six floors (Floors 78 to 83).

WTC 7 was structurally damaged by debris from the collapse of WTC 1. Photographic evidence showed that seven exterior columns were severed near the southwest corner at the lower floors. Unlike the towers, the SFRM in WTC 7 likely remained intact except for local areas around the debris impact damage at the southwest corner. All three buildings were stable with the impact damage, but the WTC 2 building section above the aircraft impact damage leaned to the east and south.

Keywords: *World Trade Center; Structural fire effects; Impact damage; Structural analysis; Failure analysis; Global collapse*

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1.0 Introduction

In 2002, the National Institute of Standards and Technology (NIST) was charged by the U.S. Congress to investigate the building construction, materials, and technical conditions that contributed to the collapse of the three World Trade Center (WTC) buildings. A sequence of analyses were performed during the NIST WTC Investigation: 1) aircraft impact analyses to estimate damage to the WTC towers, 2) fire dynamics simulations to model the spread and growth of the fires, 3) thermal analyses to predict the temporal and spatial distribution of temperature in the structures, and 4) structural analyses to simulate the response of the structure to impact and fire events and the sequence of structural failures that led to the collapse of the buildings. This paper[1] presents the data and evidence collected for the investigation, the overall strategy and interdependence of the aircraft impact, fire, thermal, and structural analyses, the collapse hypotheses developed by NIST and other researchers, and results of the analyses performed to estimate the impact damage to WTC 1, 2, and 7. An impact analysis by Purdue University is also discussed. The computed damage to the structural systems, interior walls and ceilings, and furnishings were input to the other analyses. There are three companion papers: [1] describes the buildings, [2] presents the reconstruction of the fires and thermal environment during the event, and [3] presents the reconstruction of the structural response of the WTC buildings to impact and fire damage.

What follows is a brief summary of an extensive reconstruction of the events that accompanied and followed the aircraft impact. Numerous facts and data were obtained and combined with validated computer modeling to produce an account that is believed to be close to what actually occurred. The reader should keep in mind that the buildings and the records kept within them were destroyed, and the remains of the towers were disposed of before this

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investigation began. As a result, there are some facts that could not be discerned, and there are uncertainties in this accounting. Nonetheless, NIST was able to gather sufficient evidence and documentation to conduct a full investigation upon which to reach firm findings and recommendations.

2.0 Collection of Data and Evidence

Data and evidence were collected from a number of sources, including photographs, video segments, recovered steel from WTC 1 and 2, design and shop drawings, specifications, reports, and interviews. Much of the information about the three buildings' construction was lost with the destruction of the WTC site. Nonetheless, sufficient information was obtained from drawings and specifications, reports, and available records. The data were obtained from The Port Authority of New York and New Jersey (PANYNJ), Silverstein Properties, and a number of contractors that worked on the design, construction, or modifications to the buildings. Data regarding the layout of the building interior, furnishings, and overall fuel loads were obtained from tenants and Silverstein Properties. Photographic and video evidence included debris impact damage and fire spread prior to collapse of the buildings. Over 7,000 photographs, representing more than 200 photographers, and over 300 hours of video, from professional organizations and over 40 individuals, were assembled and logged.

Steel was recovered from the WTC 1 and WTC 2 buildings, and included interior columns, exterior panels, and floor trusses, with samples of all steel strengths specified for the construction of the towers. The steel was used to determine steel properties for analysis purposes and to obtain data about the behavior of the steel in the aircraft impact and fire zones. Each piece of recovered steel had a unique stamp that gave its location within each tower. No steel was recovered from WTC 7.

Standard fire tests were conducted of the composite floors of trusses and lightweight concrete in the WTC towers at Underwriter's Laboratories [4] under contract to NIST. The tests were designed to examine the effect of scaling (furnace length is less than most floor span lengths), the floor performance for the specified spray-applied fire resistive material (SFRM) (no standard fire test of the WTC floor truss system had been previously conducted), and the effect of restraint conditions (thermally restrained and unrestrained end conditions). For assemblies with 19 mm (0.75 in) SFRM, the 5.2 m (17 ft) span had a 2 h fire rating while the 10.7 m (35 ft) span had a 1.5 h fire rating. The restrained 10.7 m (35 ft) floor system had a 1.5 h fire rating, while the unrestrained 10.7 m (35 ft) floor system had a 2 h fire rating. All the test assemblies sustained the maximum design load for 2 h without collapsing. Note that fire ratings in hours are used for design purposes, and cannot be used to predict structural performance in fire. The test results were not directly used in formulating collapse hypotheses or in the structural models, but the results established that insulated trusses could sustain full gravity loads without collapsing for a substantial period of time.

Full scale test data of structural systems under real fire conditions and realistic boundary conditions were not available in the literature to guide the development of structural models for the WTC towers or WTC 7. The largest such tests were conducted in an eight story test building with a steel braced-frame, built by the British Research Establishment within its Cardington Laboratory to conduct large, single compartment fires [5]. The typical bay size was 6 m by 9m (20 ft by 30 ft), the floor beams and girders had no fire protection, and the steel floor framing used different connection types (end plate and fin connections) from those used in the WTC buildings (fin plate, double angle, and seat connections). Such differences made extrapolation of results to the WTC buildings difficult.

Reports of uncontrolled, structurally significant fires in buildings also provided little information on structural performance during the fire events. Available building fire data from WTC 5 [6], One Meridian Plaza [7], First Interstate Bank Building [8, 9], and One New York Plaza [10] were used to support development of hypotheses and failure mechanisms for WTC 7.

The structural models of WTC 1, 2, and 7 were based on structural drawings and specifications, reports, properties of recovered steel, and visual images of the buildings prior to September 11, 2011. Evidence of the events on September 11, 2001, supported determination of the speed and orientation of the aircraft at the time of impact and the location and time of window breakage due to fire spread and growth. Such parameters were used as input to the simulations. On the other hand, visual evidence that documented the extent of damage to the buildings was used to validate the structural analyses. The simulated structural response was compared to the sequence and location of documented events, such as those listed in Tables 1, 2, and 3 [11, 12].

Table 1. WTC 1 Observed Structural Events.

Time	Face	Event Description
8:46:26	N	WTC 1 was impacted by a Boeing 767 aircraft between Floors 93 and 99. Fires started on Floors 93 to 97.
10:22:59	S	South wall bowed inward from Floor 95 to Floor 99, with a maximum inward bowing of ~1.40 m (55 in) at Floor 97.
10:28:20		WTC 1 began to collapse.

Table 2. WTC 2 Observed Structural Events.

Time	Face	Event Description
9:02:59	S	WTC 2 was impacted by a Boeing 767 aircraft between Floors 77 and 85. Fires started on the south and east sides of Floors 79 to 83.
9:21:29	E	Inward bowing of east wall, maximum deflection of 250 mm (10 in) at Floor 80.
9:53:04	E	Inward bowing of east wall, with maximum deflection of 500 mm (20 in) at Floor 80.
9:58:59	S	WTC2 began to collapse. Building section above impact area tilted mostly to the east around Floor 82 before it begins to fall.

Table 3. WTC 7 Observed Structural Events.

Time	Event Description
10:28:20 a.m.	As WTC 1 collapsed, debris struck southwest corner of WTC 7. Fires started on 10 floors near the southwest corner.
Noon to 1 p.m.	Fires were observed on Floors 19, 22, 29, 30 until 1 p.m.
~ 2 p.m.	Fires were observed spreading on Floors 7, 8, 9, 11, 12, 13.
5:20:45 p.m.	East penthouse on the roof began to descend (move) downward.
5:20:52 p.m.	WTC 7 began to collapse.

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3.0 Planning the Structural Analyses

3.1 General Analysis Strategy

Two types of nonlinear finite element analyses (FEA) were required to simulate the three buildings' behavior: pseudo-static and dynamic analyses. ANSYS [13] was selected for the pseudo-static analyses that simulated the structural response to impact damage and fire effects. Since the spatial and temporal changes in the temperature of structural members were slow relative to the dynamic characteristics (i.e., natural frequencies) of the building, the structural response to thermal loads was considered to be static in nature. The pseudo-static analysis used a non-linear static procedure with an implicit solution algorithm that guaranteed force equilibrium at each time step. LS-DYNA [14] was selected for (a) dynamic analyses of the aircraft impact effects on the towers and (b) simulation of the sequential failures in WTC 7 starting from the buckling of the first column through collapse initiation. The dynamic analyses were capable of explicitly modeling sequential failures, falling debris, and debris impact on other structural components. LS-DYNA was well suited for this type of analysis, since it can model dynamic failure processes, including nonlinear material properties, nonlinear geometry, material failures, contact between collapsing structural components, and element erosion based on a defined failure criterion. In addition, LS-DYNA can include thermal softening of materials and thermal expansion.

The finite element models for all three WTC buildings accounted for nonlinear geometric effects, temperature-dependent behavior of members and connections (including thermal expansion, stiffness, and strength degradation), and the sequential failure of structural framing and connections under fire conditions. Failure mechanisms included column buckling, composite floor failures (e.g., buckling of beams and floor truss members, shear stud failure, and slab cracking), and connection failures (e.g., bolt shear, tear out, weld failure, and loss of support). Examples of modeling approaches to incorporate failure mechanisms are given in [3].

3.2 WTC Towers

The interdependencies of the WTC tower analyses are illustrated in Figure 1. Reference structural models were developed for each building using SAP2000 software [15]. The models were used to assess the building baseline performance prior to September 11, 2001 under design gravity and wind loads [16]. The reference models served as a basis for the aircraft impact and structural response models. Reference models were developed from the structural drawings and specifications and faithfully represented the actual structures.

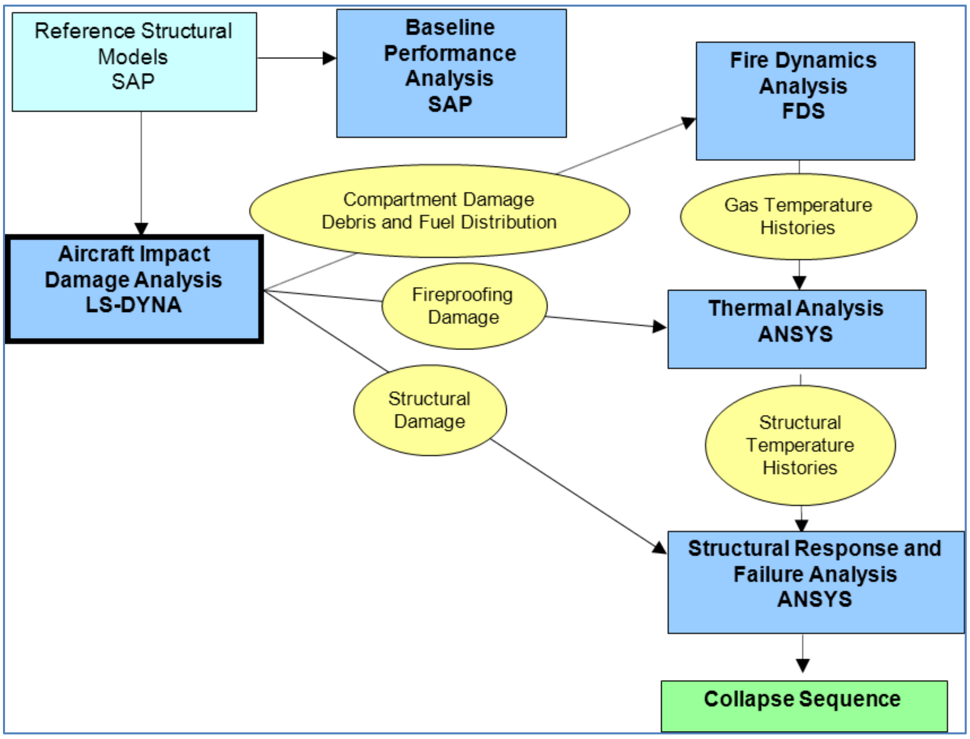

Figure 1. WTC towers analysis interdependencies [11].

The aircraft impact analyses simulated structural damage to the towers and damage to the spray-applied fire resistive material (SFRM) as debris from aircraft impact travelled at high speed through the building floor spaces. The aircraft impact simulation models included structural components and representations of the partition walls, building contents, and furnishings (modular office workstations). The analysis results included damage to the structural systems, partition walls, workstations, and structural elements. The analysis results were used to provide initial conditions to the simulations of the fire dynamics, thermal environment, and structural response. Estimates of the post-impact condition of the SFRM was based on criteria that considered damage to structural components, building partitions, and furnishings along with the debris field as calculated from the aircraft impact analyses, and is discussed in Section 6.

The fire dynamics analysis simulated the growth and spread of fires for each floor involved in fire and accounted for window breakage and damage to interior partition walls and floors (both affect ventilation conditions), and the distribution of debris and fuel. The Fire Dynamics Simulator (FDS) contained no algorithm for breaking windows from the heat of the fires. Thus, during each simulation, windows were removed at times when photographs indicated windows were first missing, see [2]. The thermal analysis provided temperature histories for structural components, based on input from the fire dynamics analyses, see [2]. The structural temperature histories, or thermal loads, and aircraft impact damage were input to the structural analyses simulating the structural response, see [3].

The WTC towers were large, complex structural systems. To include all of the structural components and connections and their associated behavior and failure mechanisms in a single finite element model would have been prohibitive analytically. To keep the global analyses tractable, the detailed multi-floor model of each building included only the impact damaged and fire-affected floors, while the remaining parts of the buildings were modeled elastically. The detailed nonlinear models of the multi-floor sections provided a quantitative assessment of fire-induced loads and thermal restraint effects within and between floors.

The analysis approach progressed from individual components to major subsystems to global systems, as indicated in Figure 2. Component analyses were conducted to identify critical behavior and failure mechanisms. The subsystem analyses incorporated the behavior and failure mechanisms from the component studies with modifications to reduce the model size and complexity, thereby enhancing computational performance without adversely affecting the quality of the results. Modeling modifications were validated against detailed component model results. Similarly, the global analyses that comprised multi-floor portions of the buildings (WTC1 and WTC 2) incorporated critical behavior and failure mechanisms identified from subsystem analyses with necessary modeling modifications to keep the solutions tractable.

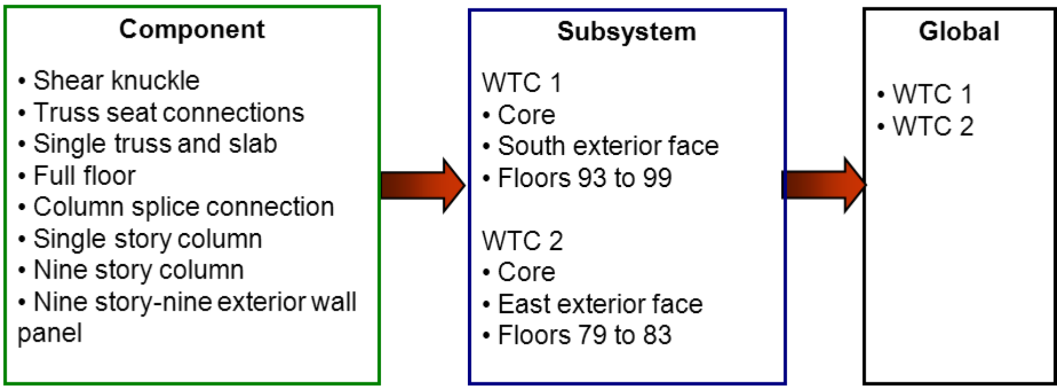

Figure 2. WTC towers structural analysis sequence [11].

Careful screening of the component and subassembly levels of the aircraft impact simulations led to identification of the following factors that were critical in estimating the level of damage to the towers: impact speed, vertical approach angle of the aircraft, lateral approach angle of the aircraft, total aircraft weight, aircraft materials failure strain, tower materials failure strain, and building contents weight and strength. These factors were assigned a range of likely values in input files for the analyses. After several preliminary global simulations, two global simulations were selected for inclusion in the four-step simulation of the response of each tower. Four fire scenarios were superimposed on the four cases of aircraft-driven damage for the fire, thermal, and structural analyses.

Multiple aircraft impact, fire, and structural analyses were conducted for each building for input data comprising the range of likely parameter values. The analyses were conducted without any adjustment of input values. To reduce the uncertainty in the multi-phase analyses, only those analyses that demonstrated fire growth and structural response reasonably similar to the observed events from photographs and videos, as illustrated in Figure 3 for the WTC towers, were continued to collapse initiation.

Uncertainty increased in the analysis results as sequential failures in components, and eventually subsystems, occurred in response to damage and fire effects over time. Uncertainty was addressed by using observed events (observables) as a constraint to reduce uncertainty in the sequence of analysis results. Figure 3 illustrates conceptually how the variance (or uncertainty) of the global stability of the towers (indicated here by the global reserve capacity (RC)) changed from the time of impact to the time of collapse. The shaded band qualitatively indicates the degree of uncertainty in RC at each time *t* after considering the analysis results and the observations made prior to *t*. The aircraft impact caused a reduction in the towers strength, but substantial reserve capacity remained afterward. The initial period of heating caused minimal changes in the structural capacity, but as time progressed, failure events caused a sudden or more rapid loss of global capacity. For instance, failure of critical columns from thermal weakening or inward bowing of an exterior wall are events associated with a rapid loss of global capacity.

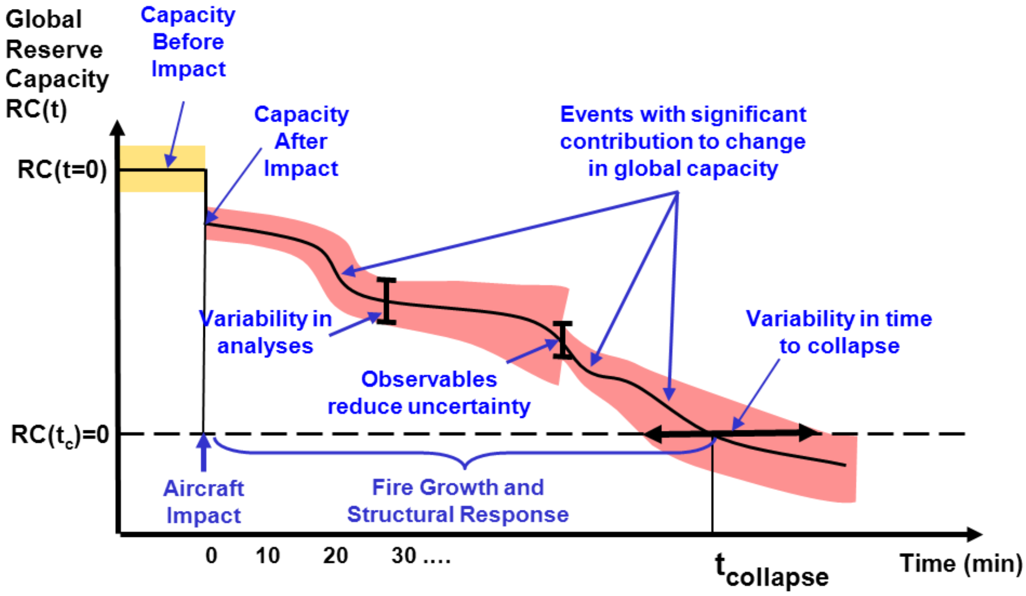

Figure 3. Schematic of the variability in simulations of global structural capacity using model predictions and observables for sequential analyses with imperfect information [11].

Aircraft Impact Models

Three separate models were developed for the impact analyses: two detailed models of the impact regions of the WTC 1 and WTC 2 towers and a comprehensive model of the Boeing 767 aircraft. All models were developed using the LS-DYNA finite element software. One of the significant challenges in developing the models was to minimize the model size while keeping sufficient fidelity in the impact zone to capture the deformations and damage distributions. The limitation for each analysis was that the combined aircraft and tower models should not exceed approximately 2.3 million nodes. The global WTC tower model and the aircraft had about 1.5 million nodes and about 0.8 million nodes, respectively. The WTC 1 model extended between floors 92 and 100, while the WTC 2 model extended between floors 77 and 85.

The towers were modeled primarily with shell elements, with the exception of the exterior wall bolted connections (beam and brick elements) and the floor truss diagonals (beam elements). The exterior columns and spandrels were modeled using shell elements with two mesh densities, a refined density in the impact zone (typically 102 mm (4 in) elements) and a coarser far field density elsewhere (typically 356 mm (14 in) elements). Brick elements were used for the bolted connections between exterior panels and beam elements were used for the bolts in the refined mesh areas. Core columns were also modeled using shell elements, with a refined typical element size of 51 mm (2 in) and a coarser typical element size of 204 mm (8 in). The floor slabs and beams within the core were modeled using shell elements. The floors slabs and trusses in the tenant areas were modeled in the refined area with shell elements for the floor slab and truss chords and with beam elements for the truss diagonals. In the far field, simplified shell element representations were used for the floor slab and trusses, with typical element sizes of 762 mm (30 in). The interior nonstructural contents of the towers were modeled explicitly. These included the partitions and workstations, which were modeled with shell elements in the path of the aircraft debris. The live load mass was distributed between the partitions and cubicle workstations.

The finite element model for the aircraft model was developed with sufficient detail to capture the mass and strength distribution of the aircraft and contents for the impact analysis. The models of the fuselage, empennage, and wing structures were developed using shell elements. Models for the landing gear and engines were developed primarily with shell elements, but used some brick elements as well. The typical element sizes were between 25 to 51 mm (1 to 2 in) for small components, such as spar or rib flanges, and 76 to 102 mm (3 to 4 in) for large parts, such as the wing or fuselage skin. Special emphasis was placed on modeling the aircraft engines due to their potential to produce significant damage to the tower components. The engine model was developed primarily with shell elements typically between 25 to 51 mm (1 to 2 in). Brick elements were used for some of the thicker hubs and the roots of the compressor blades. Fuel was distributed in the wing, based on an analysis of the likely fuel distribution at the time of impact.

Structural Models for Response to Impact and Fire

The WTC tower models were truncated several floors below the impact floors, as previous analyses showed that the structural response below the impact area remained elastic. WTC 1 was truncated at Floor 91, and WTC 2 was truncated at Floor 77. The axial stiffness of the remaining structure below the line of truncation was replaced with equivalent elastic springs.

The global models of each tower were based on the SAP2000 reference model and separate models of the core, exterior wall, and floor systems. The core columns and exterior columns and spandrels were primarily modeled with beam elements. In the core areas, floor slabs were modeled as membrane elements with a relatively coarse mesh. Effects of thermal expansion, and plastic and creep strains on column behavior were included in the global analysis. When thermally-induced strains were sufficiently large, column loads increased if they were restrained. Columns shortened and shed loads if either plastic or creep strains were large enough or if they buckled.

A finite element model of the full 96th floor of WTC 1 was translated from the SAP2000 reference models into ANSYS for detailed structural evaluations of each floor subject to aircraft impact. The floor model was primarily used beam elements for the trusses and floor beams. The floor slabs were modeled using shell elements with typical element sizes of 508 mm (20 in). The model included thermal expansion of steel and concrete members, temperature-dependent properties of steel and concrete, truss seat connections, and bowing or buckling of structural members.

Separate floor models were created from the Floor 96 structural model by imposing the different damage and temperature conditions for WTC 1 Floors 93 to 99 and WTC 2 Floors 79 to 83. Analyses of each floor affected by the aircraft impact provided input to the global tower models. A sequence of both lateral and gravity loads at each column were input to the global analyses to represent the floor response to the impact and fire conditions.

The floors in the global model were modeled with shell elements and a membrane stiffness representative of the full floor system, including the concrete slab, floor trusses, and the floor seats. Floors in the global model functioned as diaphragms and transferred loads between the exterior wall system and the core.

Bending stiffness of the floor system was not matched because the floor loads were applied at the columns. Both core and office area floor slabs were modeled with linear-elastic material properties for lightweight concrete.

The global models included removal of aircraft-damaged structural components, application of gravity loads following removal of aircraft damaged components and prior to thermal loading, temperature-dependent concrete and steel properties, and local temperature histories applied at 10 min intervals with linear ramping of temperatures between time intervals.

3.3 WTC 7

The structural analysis for WTC 7 required a two-phase approach to address both the gradual response of the structure to the fires that burned for hours and the rapid response of the structure during the collapse process (which lasted approximately 15 s).

In the first phase, a 16-story model was developed in ANSYS to determine the pseudo-static structural response to fire on Floors 7 to 9 and Floors 11 to 13, and to predict the resulting local structural failures. To improve the computational efficiency of the 16-story model, the lower seven floors and Floors 15 and 16 were replaced with “super-elements” to reduce the size of the model. Super-element is the term used for sub-structuring, where static condensation of the elastic stiffness matrix eliminates interior degrees of freedom while preserving the degrees of freedom on the boundaries of the super-element. This modification was made since these floors remained elastic, as there was no fire on these floors.

Floors 7 to 14 had detailed modeling of connections and temperature-dependent material properties. Beams and girders for floor framing and columns were modeled using beam elements with temperature-dependent inelastic material properties. Typically, the columns were meshed with 0.7 m (2 ft) long elements, and beams were meshed with 0.9 m (3 ft) long elements. The beam elements were suitable for analyzing slender to moderately stubby/thick beam structures, as they were based on Timoshenko beam theory and included shear deformation effects. Typical mesh size for the floor slab was 0.9 m x 0.9 m (3 ft x 3 ft). The floor slab was modeled using shell elements with temperature-dependent inelastic material properties. Rigid beams and user-defined elements that captured failure criteria were used to model floor framing connections and shear stud connectors. The 16-story model had approximately 100,000 elements.

The pseudo-static analysis was terminated when sufficient local failures indicated that collapse initiation was imminent. The accumulated damage due to thermally-induced failures of floor framing was input to the dynamic collapse model. The transferred data included the temperature of structural components at that time, damaged connections, and buckled beams and girders.

In the second phase, a 47-story global model representing the entire structure was developed in LS-DYNA that used structural damage from the pseudo-static analysis, the temperature state from the pseudo-static analysis, and the debris impact damage from WTC 1, as initial conditions. The model simulated the dynamic structural response from collapse initiation up to global collapse. Analysis interdependencies and uncertainty were addressed in a manner similar to that described earlier for the WTC towers.

The LS-DYNA global model was constructed mainly with shell elements, which were used to model the floor beams, girders, slabs, and columns. Typical shell element dimensions were between 0.15 m and 0.3 m (6 in and 12 in). Beam elements modeled diagonal bracing elements in the structural frame and the framing of the penthouse structures. Nonlinear discrete (spring) elements were used for the floor framing connections. Solid (brick) elements were used for some of the foundation structures and for some rigid masses representing large equipment. The 47-story model for the collapse analyses of WTC 7 had a model size of approximately 3 million elements. After gravity loads were applied to the model, debris impact damage due to the collapse of WTC 1 was applied instantaneously through the sudden removal of elements from the model. Temperatures were applied to nodes in the fire-affected zone between Floors 7 and 14. The final step in the initialization process was to apply the fire-induced damage.

4.0 Collapse Hypotheses

Hypotheses by NIST and others for the collapse of the WTC towers are presented in Section 4.1. The basis for the NIST collapse hypothesis is presented in more detail in [3]. Section 4.2 presents a brief summary of the NIST hypothesis for the collapse of WTC 7. No other collapse hypotheses for WTC 7 were found in the literature, but alternative hypotheses suggested in media reports and public forums are discussed.

4.1 WTC Towers Collapse Hypotheses

Hypotheses for structural failures and events leading to collapse were developed for each building. Photographs and videos were used to develop a timeline of events and provided information about impact damage to exterior walls, and structural events such as severed components, buckling, sagging of floors, bowing and buckling of the exterior walls, and tilting of building sections during collapse. Evaluation of the hypotheses required detailed analyses that were based on building data and evidence of events from the aircraft impact to collapse initiation.

The development of collapse hypotheses for the WTC towers reflected the stages of the investigation as data were collected and analyses were conducted. The final hypotheses developed a specific sequence for each WTC tower that identified load redistribution paths and damage scenarios for the effect of the aircraft impact and subsequent fires, and the relative roles of the columns, composite floor systems, and connections. The final collapse hypotheses considered the effects of aircraft impact damage to the structure and thermal insulation, fire growth and spread, time-varying temperatures of the structural components, and the progression of structural failures up to collapse initiation, as well as the effects of construction sequence, thermal expansion, plastic and creep strains, temperature-dependent material properties, and failure modes.

The final probable collapse sequence identified the following events for both towers. The towers were stable after the aircraft impact, but the damage to the structural systems resulted in load redistribution from interior columns to exterior columns primarily through the hat truss. Damage to passive fire protection led to rapid heating of the steel framing. The thermally-weakened floors sagged and interior columns shed loads to exterior columns. The combined effects of floors sagging and additional loads caused inward bowing of the exterior wall adjacent to the sagging floors. When loads could no longer be redistributed, collapse ensued; see [3].

The initial hypotheses were not building specific, but considered several leading hypotheses postulated by others: (1) core columns failed as they were weakened by fire, initiating overall building collapse without any contribution form the floors [17, 18, 19, 20, 21], (2) loss of floor connections resulted in impact loads on the floor below and pancaking of all floors [22], (3) thermally-induced buckling of floor trusses led to collapse initiation [23, 24] and (4) sagging floor systems led to collapse initiation through buckling of the exterior columns [25].

Bazant and Zhou [17] did not address the details of impact damage, fire dynamics, or structural response of the towers. The analysis addressed the results of prolonged heating and dynamic amplification of loads and the ability of the columns in lower floors to dissipate the falling mass of the stories above the damage. The loss of thermal insulation during impact, uniform temperatures of 800 °C (1472 °F), and creep buckling and loss of load carrying capacity in over half of the columns was assumed. The ratio of the kinetic energy of the upper building section dropping one floor to the deformation energy of plastic hinge rotation in the lower building columns was approximately a factor of eight.

Abboud, et al. [18, and as described in 19, 20, 21] used finite element analyses to calculate the aircraft impact damage to both towers and the corresponding structural response to damage and elevated temperatures. The fires were found to be less than fully developed office fires, with gas temperatures ranging from 400 °C (752 °F) to 700 °C (1292 °F) in the impact regions and well-ventilated regions near the exterior walls; exterior locations with persistent fires were assumed to have 1000 °C (1832 °F) temperatures. Based upon study of smoke plumes and fire spread, it was concluded that the floors did not fail or have a significant role in the collapse of the towers. The structural response analysis found that the impact debris dislodged thermal insulation and that the hat truss played a significant role in transferring loads between the core and exterior walls. The analysis identified the specific cause of each towers' collapse to be the failure of core columns that either lost insulation or were destroyed during the aircraft impact.

Quintiere, et al. [22] conducted a thermal analysis of floor truss web members subjected to a uniform gas temperature and a structural failure analysis based on buckling of truss web members. Gas temperatures were estimated to be approximately 900 °C (1652 °F) for the duration of the fires in each tower. A thermal analysis estimated the temperature history of the web member for two insulation thicknesses of 19 mm and 38 mm (0.75 in and 1.5 in). A web member with an assumed load was calculated to buckle when temperatures of 630 °C (1166 °F) to 770 °C (1418 °F) were reached. The time at which the insulated members reached temperatures that met the buckling criteria fell within the observed collapse time of each tower. It was noted that a bare steel web member would fail by this criteria in 10 min to 15 min, and that this time did not match the observed time to collapse initiation. Given the failure of truss web members, it was postulated that the floors would sag and fail at their connections to the columns and that progressive collapse would ensue as the floors below also failed.

Usmani, et al. [23, 24] performed a nonlinear, large displacement finite element analysis of a typical two-dimensional slice of the tower structure that encompassed twelve floors around the impact level of WTC 1. Simplifying assumptions to reduce the model complexity included restraint of lateral movement of the floor at the core column, a pinned connection to the external column, single axial elements for the truss diagonals, and no explicit modeling of connections. Core columns were assumed to be relatively cool. An exponential curve representing the time-temperature relationship was applied to the floors and exterior columns for various fire scenarios. The analysis found that the heated floors expanded and pushed the exterior columns outward. The outward movement was resisted by tension in the cool floors above and below the fire floors, so that a floor buckled when it reached approximately 400 °C (752 °F). The buckled floor truss caused the exterior column to 'rebound', resulting in large compressive loads on the floors above and below, which in turn buckled. The same mechanism propagated to adjacent floors until it was arrested or caused collapse.

Lane [25] conducted two-dimensional finite element analyses of a twelve-floor slice of the exterior column and floors to the core, a twelve-floor slice across the entire tower (from exterior column to exterior columns), and three-dimensional quarter floor, half floor, and quarter-floor seven-story section models. The analysis had no aircraft impact damage or damage to thermal insulation and did not include the hat truss; all of the models included individual floor trusses and the floor slabs. Temperatures from the fires for structural members were assumed, where the floor trusses quickly reached 800 °C (1472 °F) and the exterior columns and spandrels heated to 400 °C (752 °F) by 3600 s. Three floors were heated to 800 °C (1472 °F), when the floors sagged and the exterior wall section was pulled inward. The inward bowing of the exterior wall was considered to be the collapse mechanism for the towers.

4.2 WTC 7 Collapse Hypotheses

One of the first studies of WTC 7 [6] identified several collapse initiation hypotheses for two types of fire: (1) a fully involved floor fire that led to an internal structural failure at the lower floors on the east side of the building and (2) diesel fuel fires on the 5th floor that failed load transfer elements such as trusses or girders at the lower stories of the building. NIST considered these two hypotheses as well those suggested by others in media reports and public forums: (3) fires in the Con Edison Substation which was located in the lower three floors of the building and (4) blast hypotheses, where explosive materials would have been intentionally set to cause the collapse of the building. Analyses were conducted for each of these hypotheses, but only fires on the lower tenant floors were found to be viable, and were pursued in detailed analyses [3]. The other hypotheses were found to be unsupportable based on the analyses conducted and the evidence collected, which is summarized here.

The possibility that rupture of one of the fuel lines might have provided a continuous supply of sufficient fuel to affect a critical column or floor system was investigated. There were several emergency generator installations located on several floors which were supplied by either day tanks or pressurized loop fuel delivery systems. Simulations showed that pool fires associated with ruptured diesel fuel lines (a) would have raised the temperatures near the generators to the point where the generators would have failed, cutting off power to the fuel pumps, (b) could not raise the temperatures of the steel and concrete structure to the point of significant loss of strength or stiffness, and/or (c) would have exhausted smoke from the exhaust louvers, in conflict with the photographic evidence which showed none. The day tanks on Floors 5, 7, and 9 did not contain enough fuel to be significant contributors to the combustible load, and it was unlikely that the tanks could have been re-supplied because of multiple safeguards in the fuel delivery system. Thus, it was concluded that the hypothetical fuel oil fires on the 5th floor, or hypothetical fires on Floors 5, 7, and 9 involving day tanks, did not contribute to the collapse of WTC 7.

Scenarios of a hypothetical blast event that could have occurred in WTC 7 on September 11, 2001, were assessed, including blast location, size, and timing. Hypothetical blast scenarios with the minimum amount of required explosive were identified. Other scenarios were considered, but the amount of explosive material would have been larger. Calculations were performed to evaluate threshold explosive requirements for the windows. Four blast analyses were performed, with two charge sizes and two floor layouts. The windows would have failed on the north and east faces for even the smallest blast loading case considered (densely-partitioned layout with a 9 N or 2 lb charge). An acoustic analysis found that significant audible sound was predicted from all building faces. If propagation were unobstructed (e.g., up Greenwich Street from the north face), the sound level from all building perimeter openings at 1 km would be approximately 130 dB to 140 dB, which was not recorded in any of the videos or noted in any interviews. Details of these analyses are given in [12].

Data from three buildings with uncontrolled, structurally significant fires—One Meridian Plaza [7], First Interstate Bank [8], and the Cardington test building [5]—were also reviewed [12]. These buildings had large uncontrolled fires but no local or global collapse. All three buildings had symmetric floor framing within a rectangular grid, so that the thermal expansion of heated floors was resisted by floor sections on the opposite side of a girder or column. First Interstate Bank and One Meridian Plaza, both commercial office buildings, had fully involved fires over entire floors; the Cardington tests were a series of compartment fires. The fires in WTC 7 spread across several floors, but did not involve an entire floor at any given time. The One Meridian Plaza, First Interstate Bank, and WTC 7 building all had similar passive fire protection for Class 1B construction, with 2 h beam protection and 3 h or 4 h column protection.

The upper layer gas temperatures were likely similar in First Interstate Bank, One Meridian Plaza, Cardington tests, and WTC 7. The Cardington tests

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Fire Technology, August 11, 2012, DOI: 10.1007/s10694-012-0286-5

recorded maximum gas temperature for large, open-floor plan burning of office furnishings in the range of 1000 ºC to 1200 ºC (1800 °F to 2200 °F). These temperatures were consistent with the maximum gas temperatures of 1100 ºC (2000 °F) determined by fire simulations and measured experimentally for fires of workstations [26] similar to those in WTC 7.

If the fires in First Interstate Bank, One Meridian Plaza, the Cardington Test Building, and WTC 7 generated comparable gas temperatures, but only WTC 7 collapsed, it was hypothesized that the reason for the collapse of WTC 7, and not the other cited buildings, lay in its structural system design and the details of how the steel frames were constructed. WTC 7 sustained local damage to its exterior as a result of falling debris from the collapse of WTC 1, but this damage was found to have no effect on the collapse initiating event.

A critical look at the steel floor framing on the northeast side of WTC 7 revealed several characteristics that warranted further consideration: (1) long-span floor beams and girders on the order of 16 m (52 ft), (2) asymmetric framing (one-sided lateral support to girders), (3) absence of shear studs between the girders and slab, and (4) girder-to-column seat connections. Preliminary finite element analyses revealed that, alone or in combination, these structural features had the potential to fail during ordinary building content fires on a tenant floor.

The final probable collapse sequence identified the following events. Uncontrolled fires thermally-weakened the floor framing and resulted in floor framing failures through restrained thermal expansion. The floors in the long-span floor framing of the northeast corner collapsed, triggered a cascade of floor failures that left an unsupported interior column, which buckled. As loads transferred to adjacent columns, interior columns failed across the building interior. The much-stiffer exterior framing remained intact until the loss of lateral bracing from the lower floors caused buckling of the exterior columns and collapse ensued; see [3].

5.0 Aircraft Impact Events

Models of the WTC towers for the analysis of aircraft impact extended from Floors 92 through 100 for WTC 1 and Floors 77 through 85 for WTC 2. The multi-floor models kept the analysis tractable while maintaining sufficient fidelity in the impact zone to simulate the building response and damage distribution. Tower components in the path of the impact and debris field were represented with a fine mesh to capture local impact damage and failure, while components outside the impact zone were depicted more coarsely to capture their structural stiffness and inertial properties. The aircraft impact models included not only structural components of the towers, but also the non-structural building components such as workstations and partition walls in the path of the aircraft. A detailed model of the Boeing 767-ER aircraft was developed for the purpose of this analysis.

The aircraft impact of the WTC towers caused extensive damage to the buildings' exteriors, penetrated into the interiors causing further damage to the structural systems, dislodged insulation, and ignited multi-floor fires. The structural damage to each tower resulting from the aircraft impact was estimated using a dynamic finite element analysis. Results of this analysis were used to predict damage to the structure, fireproofing, and partition walls in the path of the debris field.

The aircraft impact analyses considered three cases for each tower, where each case had a different set of input parameters, based upon sensitivity studies [16]. From the component and subassembly simulations, it became apparent that the magnitude and location of damage to the towers could be sensitive to a number of initial conditions. Thus, it was necessary to select the factors that most influenced the outcome of a simulation. The analysis results from two cases for each tower were found to match photographic and video records reasonably well and were selected for further fire dynamics, thermal, and structural analyses. These cases for each tower were referred to as Cases A and B for WTC 1 and Cases C and D for WTC 2. The analysis parameter values for all four cases are shown in Table 4. Cases A and C represented the best estimate of the various parameters (100 percent of the parameter value) while Cases B and D represented a more severe scenario where selected parameters were adjusted to result in higher damage to the towers. Cases B and D simulations of aircraft impact more closely approximated the observed damage to the exterior of the towers, so these cases were selected for the next phase of analysis.

Table 4. Input parameters for global impact analyses.

Analysis Parameters		WTC 1		WTC 2	
		Case A	Case B	Case C	Case D
Flight Parameters	Impact Speed	198 m/s (443 mph)	211 m/s (472 mph)	242 m/s (542 mph)	255 m/s (570 mph)
	Vertical Approach Angle	10.6°	7.6°	6.0°	5.0°
	Lateral Approach Angle	180.0°	180.0°	13.0°	13.0°
Aircraft Parameters	Weight	100 %	105 %	100 %	105 %
	Failure Strain	100 %	125 %	100 %	115 %
Tower Parameters	Failure Strain	100 %	80 %	100 %	90 %
	Live Load Weight[a]	25 %	20 %	25 %	20 %
	Contents Strength	100 %	100 %	100 %	80 %

a. Live load weight expressed as a percentage of the design live load.

6.0 The Immediate Damage

6.1 WTC 1

American Airlines flight 11 flew almost straight toward WTC 1 (Figure 4), with the right wing elevated approximately 25° and descending at an angle of about 10° at impact [16]. At 8:46:30 a.m. eastern daylight time (EDT), the nose hit the 96th floor and cut a gash that was over half the width of the building and extended from the 93rd floor to the 99th floor (Figure 5). The structural damage included damaged floor systems and severed exterior and core columns. In addition, SFRM was stripped from steel members as the debris from aircraft impact travelled at high speed through the building.

Estimates of the post-impact condition of the passive fire protection was based on criteria that considered damage to structural components, building partitions, and furnishings along with the debris field as calculated from the aircraft impact analyses, such as that shown in Figure 6. SFRM on floor trusses was considered dislodged when the debris impact was sufficient to damage or destroy room furnishings (modular office workstations) in the same area of the affected floor, as illustrated in Figure 7. If the room furnishings remained intact, then the insulation on the steel trusses above these furnishings was assumed to remain intact. If the room furnishings were damaged or destroyed by the debris field, then the insulation on the steel trusses above these furnishings was assumed to be dislodged. The fireproofing damage estimates were conservative as they ignored possibly damaged and dislodged fireproofing in a much larger region that was not in the direct path of the debris.

Core columns were thermally protected with SFRM, gypsum wallboard enclosures, or a combination of both. SFRM was assumed to be dislodged from columns if the direct debris impact failed wall partitions in the immediate vicinity. The representative bending strength of building partitions in the impact simulations was 3.5 N/mm^2 (500 psi), while the representative adhesive and cohesive strength of SFRM measured in the laboratory by NIST was generally less than 0.08 N/mm^2 (12 psi) [27]. Gypsum column enclosures were assumed to have a lesser representative strength than wall partitions.

The damage over the affected floors is shown in Figure 8, which includes observed exterior damage and estimated interior damage based on aircraft impact simulations [28]. Of the 59 exterior columns, 35 were severed and two were heavily damaged (severe damage such that the column could no longer carry its loads). Of the 47 core columns, six were severed and three were heavily damaged. Partitions were damaged and SFRM was dislodged by direct debris impact over five floors (Floors 94, 95, 96, 97, and 98) and included most of the north floor areas in front of the core, the core, and extended to the some south floor areas. It was estimated that 43 of 47 core columns were stripped of SFRM on one or more floors. SFRM was also stripped from floor trusses covering 5,600 m^2 (60,000 ft^2) of floor area.

WTC 1 was stable after the aircraft impact, as the gravity loads from severed and damaged core columns transferred to adjacent intact core columns and to exterior columns through the hat truss at the top of the building [11]. Figure 9a shows the hat truss framing with the core structure; Figure 9b shows the vertical displacement of the exterior framing after the aircraft impact. At Floor 99, the vertical displacements increased from 63 mm (2.5 in) for gravity loads to about 145 mm (5.7 in) after the aircraft impact.

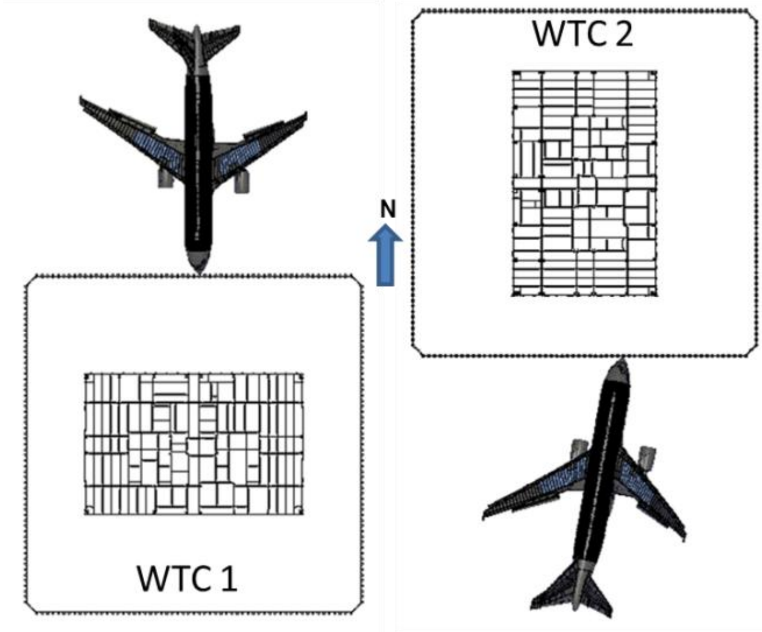
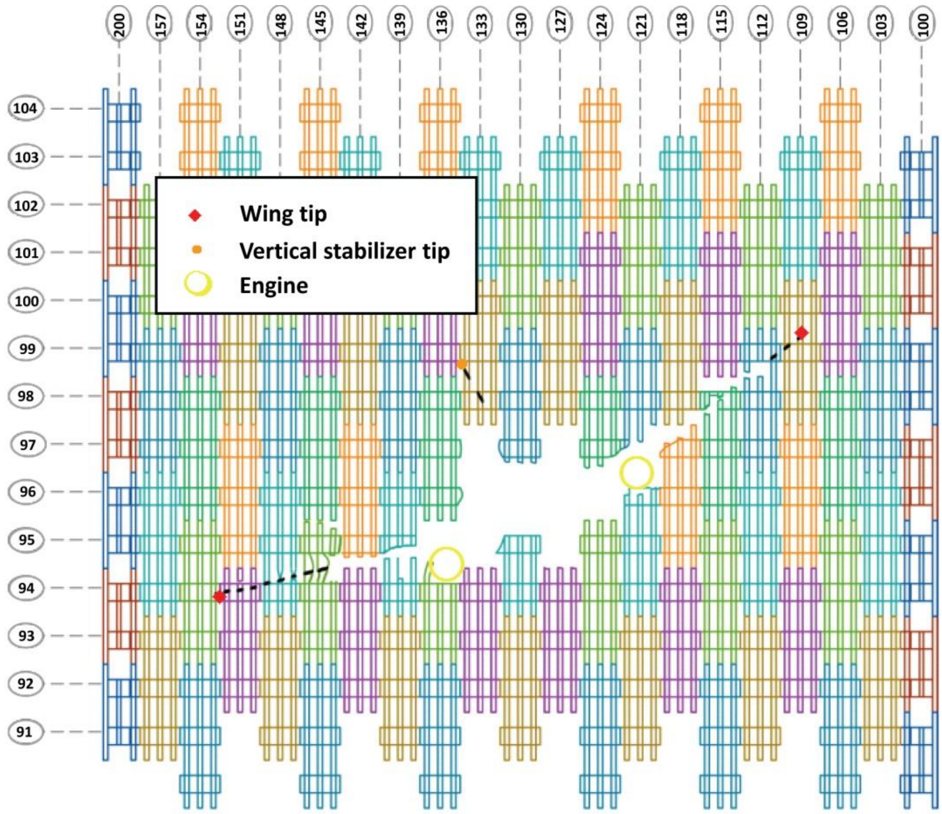


Figure 4. Aircraft impact conditions for WTC 1 and WTC 2 [15].



Floor numbers on the left point to the floor slabs. Top numbers refer to exterior columns. The colors distinguish the individual three-column-wide, three-story-tall façade sections.

Figure 5. WTC 1 south face damage with key aircraft component locations marked [27].

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Fire Technology, August 11, 2012, DOI: 10.1007/s10694-012-0286-5

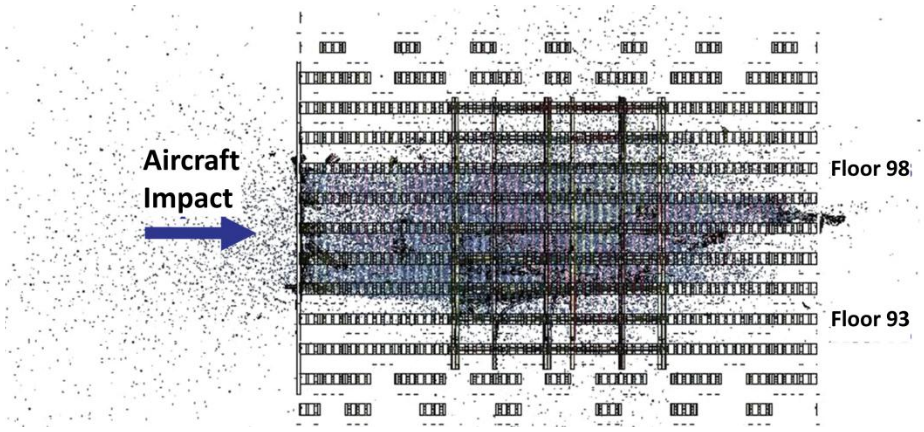

Figure 6. Debris and fuel field in WTC 1 analysis of aircraft impact [27].

Figure 7. Damage to partitions and furnishings in WTC 1 analysis of aircraft impact to floor 95. Overlay shows extent of estimated dislodged SFRM [11].

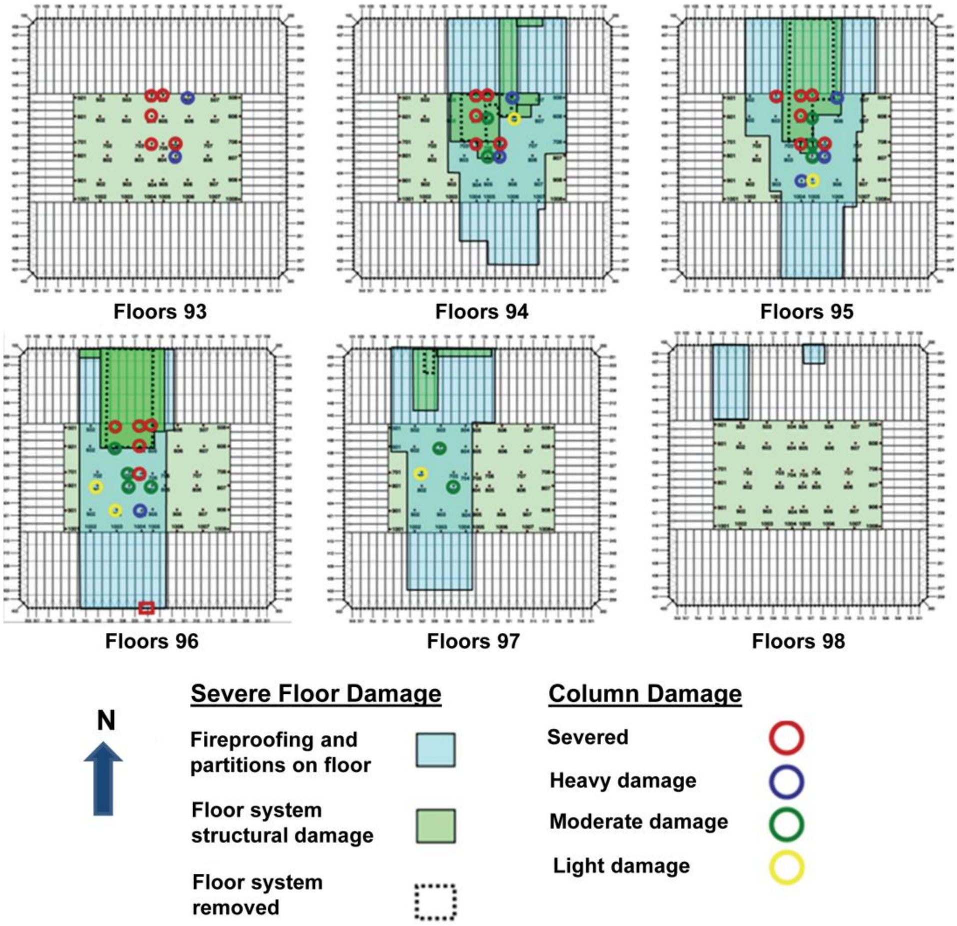

Figure 8. WTC 1 aircraft impact damage based on simulations [11].

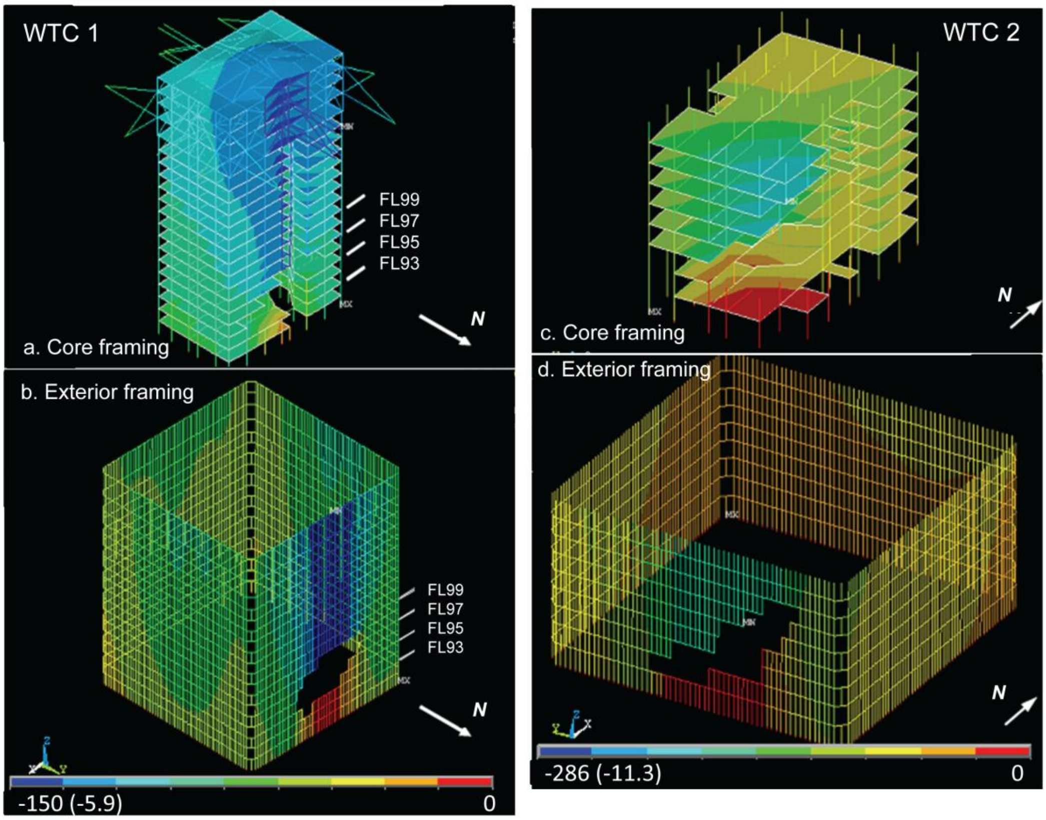

Figure 9. Vertical displacement in mm (in) based on aircraft impact simulations [11].

An independent detailed finite element analysis of the aircraft impact on WTC 1 was conducted by [29]. Similar to the NIST models, three-dimensional, detailed models of the aircraft and the upper section of WTC 1 building were developed based on available documents and records. Taking into account the uncertainties inherent in such simulations, significant damage to the core structure was found to be in the 95th through 97th stories of the tower. The results also indicated that as the aircraft debris went through several stories in the tower, much of the thermal insulation on the core columns would have been dislodged. It was estimated that a core collapse mechanism could have been initiated in WTC 1 if the core column temperatures reached approximately 700°C due to the ensuing fire. The authors concluded that impact damage to the core structure had a negligible effect on the critical thermal load required to initiate collapse in the core structure.

6.2 WTC 2

United Airline Flight 175 hit the south face of WTC 2 about 7 m (23 ft) east of the center of the 81st floor slab, heading about 15° to the northeast at

9:02:59 a.m. EDT [16]. The off-center impact twisted the upper part of the tower in a counterclockwise movement. The building vibrated in the north-south direction, along with a twisting motion, with the amplitude decreasing steadily with each oscillation. The right wing was elevated 38 degrees, and the aircraft was heading 6 degrees downward. This entry wound stretched from Floor 77 to Floor 85 (Figure 10).

As shown in Figure 11, structural damage similar to that of WTC 1 occurred, but the damage was concentrated on the east side of the building. WTC 2 was stable after the aircraft impact, but the building section above the aircraft impact damage leaned to the east and south.

Of the 59 exterior columns, 33 were severed and one was heavily damaged. Of the 47 core columns, ten were severed and one was heavily damaged. Partitions were damaged and SFRM was dislodged by direct debris impact over six floors (Floors 78, 79, 80, 81, 82, and 83) and included the south floor area in front of the core, the central and east regions of the core, and most of the east floor area, extending to the north wall. It was estimated that 39 of 47 core columns were stripped of SFRM on one or more floors. SFRM was also stripped from floor trusses covering 7,400 m^2 $^($80,000 ft^2) of floor area.

Ten core columns were severed and one core columns was heavily damaged (severe damage such that the column could no longer carry its loads). Partitions were damaged and fireproofing was dislodged by direct debris impact over six floors (Floors 78, 79, 80, 81, 82, and 83) and included the south floor area in front of the core, the central and east regions of the core, and most of the east floor area, extending to the north wall. The gravity loads from the severed and damaged core columns were transferred to the exterior walls through the hat truss [11]. The vertical displacements in the core and exterior walls following the impact are indicated in Figure 9c and 9d, respectively. At Floor 86, vertical displacements increased from approximately 63 mm (2.5 in) for gravity loads to 188 mm (7.4 in) on the south face and to 254 mm (10 in) in the core after aircraft impact.

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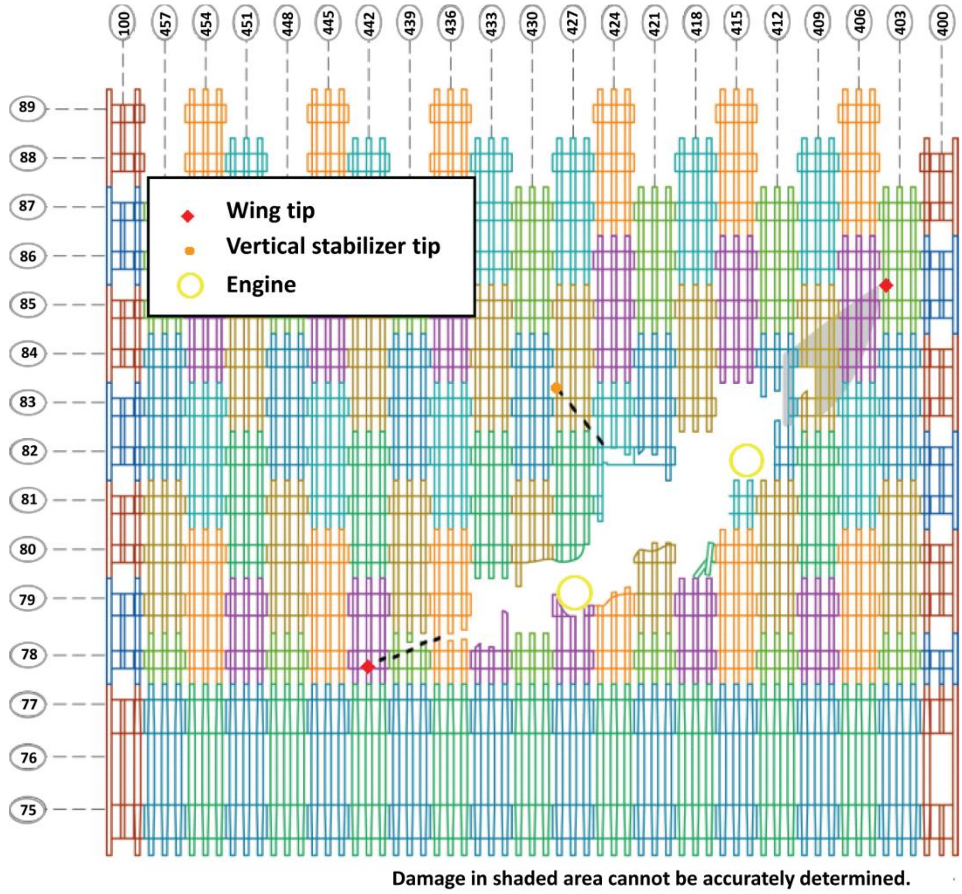
Fire Technology, August 11, 2012, DOI: 10.1007/s10694-012-0286-5



The colors distinguish the individual three-column-wide, three-story-tall façade sections.

Figure 10. WTC 2 south face damage with key aircraft component locations marked [27].

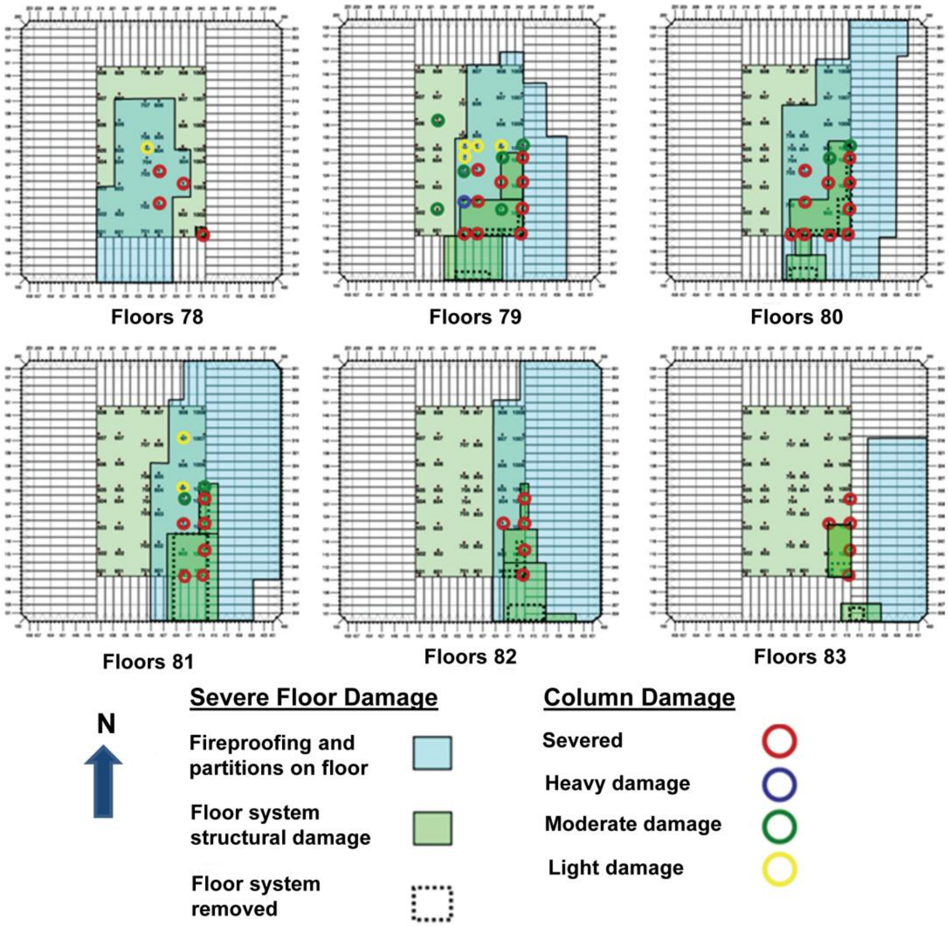


Figure 11. WTC 2 aircraft impact damage based on simulations [11].

6.3 WTC 7

WTC 7 was structurally damaged by debris during the collapse of WTC 1 at 10:28:22 a.m. EDT. Photographic evidence showed that seven exterior columns were severed near the southwest corner at the lower floors, as shown in Figure 12. Unlike the towers, the SFRM in WTC 7 likely remained intact except for local areas around the debris impact damage at the southwest corner. Available documents, photos, and accounts indicated that the condition of the SFRM in WTC 7 was adequate and well-maintained. Inspection of the Deutsche Bank, which had the same type of SFRM and was locally damaged by falling debris from WTC 2, found that only the immediate impact area had damaged SFRM.

The damage to the exterior of WTC 7 was used to estimate a range of interior damage to the structure and SFRM. The interior damage estimates were limited to the immediate vicinity of the WTC 1 debris impact, based on the structural framing features and similar findings in the Deutsche Bank building.

WTC 7 remained stable after the initial damage by debris impact from WTC 1. Loads from severed exterior columns were redistributed to adjacent columns through the spandrel beams. The vertical displacements above the damage area were on the order of 200 mm (8 in), as shown in Figure 12.

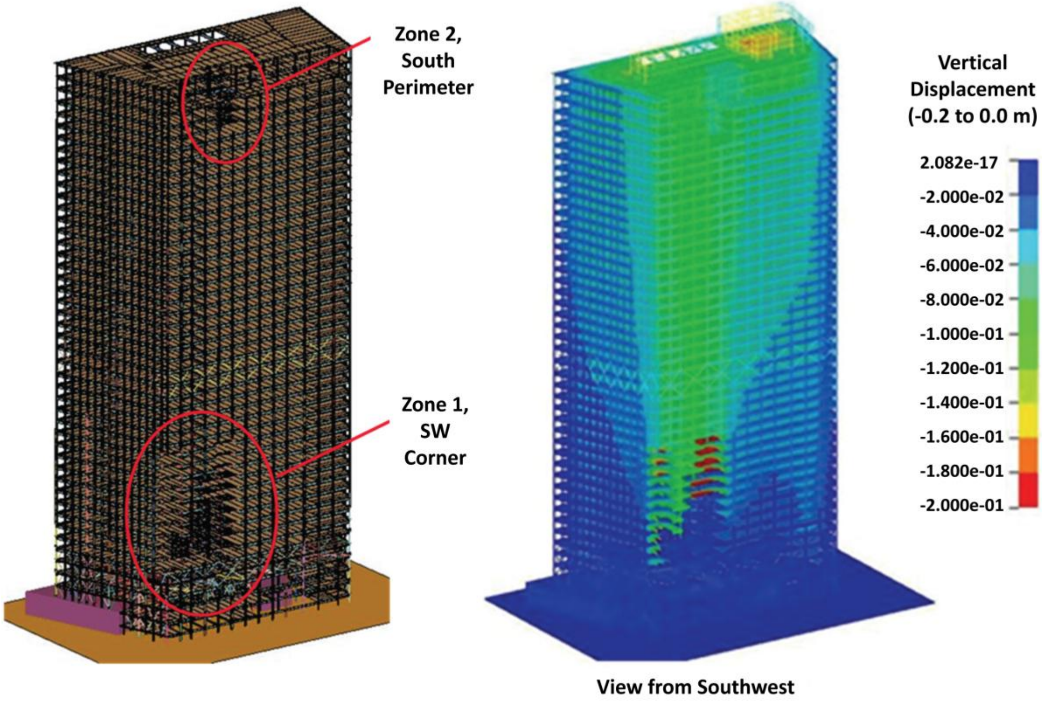


Figure 12. WTC 1 debris impact damage applied to WTC 7 model (left) and simulated vertical displacement (right) [12].

7.0 Summary

7.1 Collapse Hypotheses

Initial collapse hypotheses for the WTC towers considered several leading hypotheses postulated by others: (1) core columns failed as they were weakened by fire, initiating overall building collapse, but the floors played no role, (2) loss of floor connections resulted in impact loads on the floor below, followed by pancaking of all floors, (3) thermally-induced buckling of floor trusses led to collapse initiation and (4) sagging floor systems led to collapse initiation through buckling of the exterior columns.

The final hypotheses had specific sequences for each WTC tower that identified load redistribution paths, damage from the aircraft impacts, fire growth and spread, and the relative roles of the columns, composite floor systems, and connections in carrying and redistributing gravity loads. The final hypotheses were based on detailed finite element analyses, including the time-varying temperatures of the structural components based on a detailed fire analysis, and the progression of structural failures that led to collapse initiation, see [3].

Other collapse hypotheses, and their supporting analyses, were reviewed. The analyses by others generally did not include structural damage from the aircraft impact, used assumed time-temperature curves, and conducted analyses of components or subsystems (i.e., floor trusses and exterior columns). The exception was the analyses by Abboud et al [18], which included structural impact damage, assumed time-temperature curves, and conducted global analyses of each tower. Based on the global analyses, Abboud et al was able to capture subsystem responses and interactions that occurred during the fire exposure, such as the heating of core columns with dislodged SFRM and the role of the hat truss in transferring loads between the core and exterior columns.

The global analyses by NIST (see [3]) and Abboud [18] demonstrate that (1) component analyses are unable to capture the response of a structural system to a significant fire and (2) an analysis is required that includes all subsystems that may be affected by load redistribution from thermal effects, such as restraint of thermal expansion or thermally reduced material properties.

For WTC 7, the following collapse hypotheses were considered: (1) fully involved fires on lower tenant floors led to an internal structural failure, (2) diesel fuel fires on the 5th floor failed load transfer elements, (3) fires in the Con Edison Substation and (4) blast hypotheses, where explosive materials would have been intentionally set to collapse the building. Analyses were conducted for each of these hypotheses, but only fully-involved fires on the lower tenant floors were found to be viable. Preliminary finite element analyses indicated that, alone or in combination, the following structural features had the potential to fail during fully-involved fires: (1) long-span floor beams and girders on the order of 16 m (52 ft), (2) asymmetric framing (one-sided lateral support to girders), (3) absence of shear studs between the girders and slab, and (4) girder-to-column seat connections. These features and failure modes were included in the final global analyses of the structural response to impact damage and fire, see [3].

7.2 Impact Damage

In general, observed exterior impact damage was used to validate the aircraft impact analyses for the towers. For WTC 1 and 2, the aircraft impact analyses considered three cases for each tower, where each case had a different set of input parameters that bounded reasonable values for the aircraft impact. The aircraft impact analyses were then used to estimate the extent of the interior damage to the structural elements, furnishing, and SFRM.

The observed exterior damage to the structure and cladding of WTC 7 was used to estimate a range of interior damage to the structure and SFRM. The interior damage cases were limited to the immediate vicinity of the WTC 1 debris impact, based on the structural framing features and similar findings in the Deutsche Bank building.

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