Development of WTC 7 Structural Models and Collapse Hypotheses

Draft Statement of Work

Background

The National Institute of Standards and Technology (NIST) is conducting a federal building and fire safety investigation of the World Trade Center (WTC) disaster. More information about NIST's investigation may be found at the NIST Web site http://wtc.nist.gov. NIST is investigating the building construction, the materials used, and the technical conditions that contributed to the outcome of the WTC disaster. The primary objectives of the NIST-led investigation are to:

1. Determine why and how the 110-story WTC 1 (the North Tower) and WTC 2 (the South Tower) collapsed following the initial impacts of the aircraft and why and how the 47-story WTC 7 collapsed;
2. Determine why the injuries and fatalities were so high or low depending on location, including all technical aspects of fire protection, occupant behavior, evacuation, and emergency response;
3. Determine what procedures and practices were used in the design, construction, operation, and maintenance of WTC 1, 2, and 7; and
4. Identify, as specifically as possible, areas in building and fire codes, standards, and practices that are still in use and warrant revision.

The NIST investigation includes eight projects that provide the focus of the technical work. Information about these projects is included in the NIST Plan for the National Building and Fire Safety Investigation of the World Trade Center Disaster, which may be found at the NIST Web site http://wtc.nist.gov/media/WTCplan_new.htm.

This solicitation contributes to completion of the first primary objective of the investigation and the objectives of Project 6 (Structural Fire Response and Collapse). Specific information may be found at the NIST Web site http://wtc.nist.gov/media/WTCplan_new.htm#proj6 under Project 6, Task 6 of the Final Plan. Project 6 seeks to determine the structural response of the World Trade Center Building 7 (WTC 7) to impact by debris from the collapse of WTC 1, the fire environment, and any other events that may have occurred, and to identify probable structural collapse mechanisms.

This Statement of Work (SOW) describes analyses that support determination of the location and cause of the initiating event (i.e., the first component or group of components that failed in WTC 7) that led to global collapse, and the subsequent series of component and subsystem failures up to global collapse (including the vertical and horizontal progression of failures up to the point of global instability) that are consistent with the observations from video and photographic records and other evidence.

WTC 7 was a 47 story building with mechanical penthouses on the roof. Floors 1 to 7 varied in their design and construction, and included transfer trusses and girders in the mechanical area

and a perimeter belt truss at Floors 5 and 6. Floor 5 was constructed with a 14-in. slab reinforced with WT-shapes. Floor 7 was constructed with an 8-in. slab with bar reinforcement. Floors 5 and 7 transferred lateral loads from the exterior wall to the core. Floors 8 to 46 were tenant occupied and had nearly uniform design and construction features.

The analyses in this SOW include detailed full floor analyses and global analyses. The detailed floor analyses will determine likely modes of failure for Floors 8 to 46 under support removal due to failure of one or more columns (at one or more locations), and aid the development of a less refined model for use in the global analyses. Two types of global analyses will be conducted. Sensitivity studies will determine the response of WTC 7 to various scenarios of initiating events. Final global analyses will support the determination of the location and cause of the initiating event, by incorporating data from NIST for simulating the initiating event (see Data Requirements below), as well as the location and cause of subsequent failures that led to global collapse.

Data Requirements

NIST will supply a list of observations for validation of analysis results. Such information includes damage to the structural system by debris from the collapse of the WTC towers and a timeline of structural observations from videos and photographs, interviews, and other documents. Appendix L of the June 2004 Progress Report on the Federal Building and Fire Safety Investigation of the World Trade Center Disaster contains the observations and timelines known at that time, and is attached as Appendix A to this SOW. Information obtained or developed subsequently has not substantially changed the observations or timeline.

NIST will supply estimates of temperature-dependent mechanical properties, including the modulus of elasticity, yield stress, ultimate tensile stress, and creep strain. The data supplied will represent best estimates based on plans, specifications, and examination of steels similar to those used in WTC 7. The Contractor is not expected to conduct independent testing of materials.

The presence of fuel tanks and the fuel distribution system will be considered by NIST in conducting fire dynamics analyses. The Contractor is not expected to conduct independent fire dynamics analyses, heat transfer analyses, or investigation of the fuel system.

NIST will conduct in-house fire, thermal, and structural response analysis to determine how and why the initiating event occurred with a detailed model that includes the 5th to the 13th floors. The results of this analysis will be combined with the results of the analyses described in this SOW to determine the probable initiating event and collapse sequence. NIST will also investigate the possibility of any other events that may have occurred that day. NIST will provide data for debris damaged members and fire effects on the members identified in each initiating event that is analyzed. NIST will work with the contractor to determine a suitable approach for transferring elevated temperatures, temperature effects, stresses, and deflections. Possible approaches include providing temperature data for structural model nodes or member data for equivalent member properties, (e.g., area, inertia, etc.) to represent heating effects, column buckling, or other structural responses. The contractor can select to use either thermally-

[1]Review of photographic and video evidence led to the location of the initiating event in the working hypothesis being located below the 14th floor on the east side of WTC 7, as described in Appendix A.

induced properties of members or time-dependent temperature data at the nodes in the structural model. The contractor will be required to estimate the loading input data of any other scenarios selected for initiating events, based on studies conducted by NIST and selected experts.

Previous Analyses

Previous analyses were conducted by NIST as part of the WTC Investigation. The work will be made available to the Contractor as background information. The work of the Contractor shall not be limited by these models, hypothesis, or analysis results. A working collapse hypothesis is described in the June 2004 Progress Report on the Federal Building and Fire Safety Investigation of the World Trade Center Disaster (Volume 1, pg 17), as follows:

- An initial local failure at the lower floors (below floor 13) of the building due to fire and/or debris induced structural damage of a critical column (the initiating event), which supported a large span floor bay with an area of about 2,000 ft^2,

- Vertical progression of the initial local failure up to the east penthouse, as large floor bays were unable to redistribute the loads, bringing down the interior structure below the east penthouse; and

- Horizontal progression of the failure across the lower floors (in the region of floors 5 and 7 that were much thicker and more heavily reinforced than the rest of the floors), triggered by damage due to the vertical failure, resulting in disproportionate collapse of the entire structure.

This hypothesis may be supported or modified, or new hypotheses may be developed through the course of this study.

Previous models and analyses included:

- Identification of events and data from photographs, videos, and witness accounts.
- Studies of fire spread and growth on Floors 5, 7, and 8.
- Studies of heat transfer to Core Columns 79, 80, and 81 on Floors 5, 7, and 8.
- SAP2000 linear global model of WTC 7, which was based on structural drawings, that included beam elements for columns and floor beams, and representative shell elements for reinforced concrete floor slabs. The model was evaluated for design gravity and wind loads, service gravity loads, and stability for damage conditions caused by debris impact.
- Studies of Core Column 79 (see Appendix A) response to elevated temperature profiles for collapse initiation, using Mathcad calculations and an ANSYS shell element model.
- SAP2000 model of a single floor model representative of Floors 8 to 46. The floor model was more detailed than the floors in the global model; plastic hinges were added at specific locations to beams and columns. Core columns support was removed (i.e. Columns 76 to 81 were removed individually in separate analyses) to determine the mode of floor failure as part of the analysis of the vertical progression of failure.
- SAP2000 model for the horizontal progression analyses of failure across the lower core columns. The model was extracted from the global model and plastic hinges were added at specific locations to beams and columns. The horizontal progression was analyzed by

removal of components or application of an action resulting from a failure of Floor 5 or Floor 7.

- SAP2000 kinematic model (frame elements with all beam-columns connections assumed to be pinned) was used to evaluate the effect of assumed column failures and determine the resulting deformed shape of the structure.

The models will be made available to the Contractor for use as appropriate. The input files have been updated to SAP2000 version 10.

Objective

The objective of this solicitation is (1) to conduct analyses that support the determination of the location and cause of the initiating event and the probable collapse sequence, in conjunction with parallel NIST analyses, and (2) to validate the results with observations from video and photographic records and other evidence.

Scope of Work

In this scope of work, the determination of the location and cause of the initiating event is given primary importance. The sequence of failures following the initiating event that led to global collapse, while also important, is dependent upon the proper identification of the initiating event. While the sequence of failures following the initiating event may be adequately addressed with less detailed analyses, the analyses must be of sufficient rigor to support the identification of the probable sequence of failures.

For all tasks included in this solicitation, the models, assumptions, and analyses will be subject to review and approval by NIST. NIST will arrange for third parties to conduct independent reviews before final approval. NIST plans to retain a third party expert in structural system behavior, structural stability, and failure criteria for members and system failure. The third party expert will provide expert technical assistance to guide and assist the Contractor's work, but it is the Contractor's responsibility to conduct the work described in this SOW. Third party experts will also review Contractor reports for: (1) appropriateness of the models for their intended uses, including modeling assumptions, level of detail, model geometry and material properties, and verification and validation procedures; and (2) appropriateness of the analyses and accuracy of results.

The Contractor shall provide the labor and materials necessary to perform the tasks described below.

Structural analysis of initiating event and failure sequences leading to global collapse initiation

Task 1. Floor Component and Subsystem Analyses. The Contractor shall conduct analyses of a three-dimensional detailed floor model, representative of tenant Floors 8 to 46, which account for steel framing, concrete slabs, steel decks, slab reinforcement, connections, and service gravity loads (dead load plus service live load). Analyses shall be conducted to meet the following subtasks:

a. Identify an appropriate steel and concrete constitutive model for the composite floors and an appropriate representation of the concrete slab, reinforcement, and the steel deck for use in the floor model in Task 1b and 1c.

b. Determine the floor response under service gravity loads to various initiating event scenarios through member removal, or other appropriate approach, to determine the dynamic response and stability of the floor system for each postulated initiating event. The contractor shall conduct up to 20 analyses to determine the effect of removing selected columns, either individually or simultaneously, and shall identify locations and modes of possible floor failure. The selected columns shall have gravity loads applied that represent loads from the upper stories. The contractor shall work with NIST to identify the columns or group of columns selected for removal.

c. Develop an equivalent representation of the tenant floors for the global model that captures possible failure modes with a coarser mesh, with the intent of reducing global model run time with minimal loss of accuracy of structural behavior or failure modes. The structural response of the coarser floor model for the global finite element analyses shall be compared with that of the detailed floor model used for Task 1b to demonstrate equivalent behavior.

The tenant floor model shall include a detailed finite element mesh and consider inertial effects and nonlinear responses, such as load redistribution, concrete slab cracking, large floor deflections, yielding, plastic hinge formation, connection failure, and floor instability.

The Contractor may use the SAP2000 floor model developed previously as a basis for developing the nonlinear floor model(s) in this contract. The Contractor shall demonstrate the model equivalence to the SAP2000 linear global models for deflections and member stresses for the design dead and live load case. Discrepancies in loads or deflections for a linear analysis exceeding 1 percent shall be addressed by either adjusting the model within appropriate bounds or by explaining the source of the difference to NIST's satisfaction.

Task 2. Global Analyses. The Contractor shall conduct analyses of a three-dimensional global model of WTC 7 under service gravity loads (dead load plus service live load) to determine the structural response of WTC 7 to different initiating events. Analyses shall be conducted to meet the following subtasks:

a. Determine global structural stability for two damage states, caused by debris impact during the collapse of WTC 1. NIST will estimate the two states of damage to the structural system, based on witness accounts and photographs, and provide the estimates to the contractor. The analyses shall be conducted to characterize the mechanism by which loads redistributed after the impact damage from falling debris.

b. Conduct a sensitivity study where up to 20 initiating events are analyzed, through member removal, or other appropriate approach, to determine structural stability following the loss of support and the sequence of member failures that result from a given scenario. The contractor shall work with NIST to identify various initiating event scenarios, based on the detailed floor analysis results that best match observations of building performance.

c. Conduct final analyses that simulate the initiating event, whether due to fire or other effects, and the subsequent failure sequence up to global collapse (including the vertical and horizontal progression of failures up to the point of global instability). The contractor shall work with NIST to identify up to five scenarios, based upon the results of Task 2b, the NIST analyses of structural response to fires, and plausible other scenarios identified by NIST. NIST shall provide data for fire effects for the affected areas in a format agreed to by NIST and the contractor. Data for fire-induced member degradation can be either (1) elevated temperature history data for structural nodes or (b) an equivalent representation (i.e., reduction of member properties, area, inertia, etc., that represent heating effects or inelastic column buckling). If creep is found to be significant, based on NIST analyses of the initiating event, an appropriate method to address creep effects shall be included by the Contractor. If other cases are selected for the initiating event, the contractor shall determine loading input data required for such scenarios. The final analyses shall be conducted to determine, in conjunction with NIST:

    1. a time sequence of events, from the initiating event up to global collapse,
    2. the mode of failure for each critical member in the sequence,
    3. load redistribution paths during the sequence of events, and
    4. a table comparing analysis results with observations.

The global model shall include a detailed finite element mesh below approximately floor 14^2, sufficient to account for the steel framing, concrete slabs, steel decks, reinforcement, and connections. The remainder of the structure shall include the steel framing and either concrete shell elements or a constraint representation (i.e., if the slab can be shown through the floor analyses results to play little role in the transfer of load between columns), with sufficient detail to analyze the nonlinear response of the upper structure to the initiating event and the subsequent progression of failures up to global collapse.

Analysis of structural stability in Task 2 shall include nonlinear structural responses, such as load redistribution, p-delta effects, yielding, plastic hinge formation, large deformations, local buckling, inelastic column buckling, creep, and sequential member failures. The final analyses in Task 2c shall include the same nonlinear structural responses as Tasks 2a and 2b, as well as appropriate features for modeling the initiating event and the subsequent progression of failures up to global collapse. Reduced levels of modeling detail may be used in areas that are not subject to anticipated member failure or other nonlinear behavior or that can be shown to capture essential behavior by comparison with more detailed models.

The Contractor may use the SAP2000 global model or submodels as a basis for developing the nonlinear model(s). The Contractor shall demonstrate the global model equivalence to the SAP2000 linear global models for deflections and member stresses for the design loads. Discrepancies in loads or deflections for a linear analysis exceeding 1 percent shall be addressed by either adjusting the model within appropriate bounds or by explaining the source of the difference to NIST's satisfaction.

Reporting

The contractor shall prepare reports that clearly describe the details of the final models, analytical approach and procedures, element features, constitutive models, analysis assumptions, and results, with sufficient detail to allow other professionals to understand completely the analyses conducted and the results obtained. Results of the structural response and collapse initiation analyses shall be presented graphically to illustrate the description of analytical procedures and results. NIST will provide MS Word report templates which shall be used for report preparation. Electronic files of the reports shall be provided to NIST in MS Word.

The Contractor shall produce high-quality graphics and animations of the initiating event and the sequence of component and subsystem failures, up to global collapse (including the vertical and horizontal progression of failures up to the point of global instability).

Input files for numerical analyses shall be annotated to clearly describe the data and any appropriate comments regarding assumptions or simplifications. All final input files shall be delivered to NIST on a CD.

Deliverables shall not include findings, conclusions, and recommendations. This contract involves tasks that include data collection, data processing, fact-based analysis, and use of commercial or proprietary computer models or software.

Government Furnished Information (GFI)

The GFI dates are relative to the notice to proceed (NTP).

Item	GFI	Format	Date
1	Structural, architectural, and mechanical drawings.	Drawings on CD or printed copies	At contract award
2	Two estimates of damage to structural members from debris impact during the collapse of WTC 1.	Electronic data files	6 weeks
3	Initial list of observed data from events of 9/11/01 to be used in evaluating models and analysis results.	Electronic data files	6 weeks
4	Estimates of design and service loads.	Electronic data files	At contract award
5	Mechanical properties of all steel and concrete.	Electronic data files and/or reports	At contract award
6	Access to NIST's WTC databases, including photographic and video evidence, and other applicable information, which includes computations for significant tenant alterations, photographs during construction, project correspondence and files, and specifications.	NIST Database reports and queries	At contract award
7	MS Word Template for report preparation.	Electronic data files	At contract award

8	Summaries and results of previous analyses conducted on WTC 7; SAP2000 models (Ver. 10 release).	Electronic data files	At contract award
9	Data for fire or other effects for identified members for Task 2c, in a format agreed to by NIST and the contractor.	Electronic data files and/or reports	TBD at contract award

Government Furnished Equipment

If needed, NIST will make available to the contractor remote access to the following multiple-processor computing resource throughout the duration of the contract. The contractor may use this computing resource for numerical calculations, but not for pre- or post-processing of the data:

> Up to 36 AMD Athlon MP 2000+ CPUs on a LINUX cluster. Each node in the cluster is a dual processor with 1 gigabytes of memory per CPU. The machines will provide the Contractor up to 6 gigabyte of disk storage.

The Contractor shall indicate if they plan to use the computer facility. If the contractor has a need for additional computing resources (such as number of processors, disk storage, or CPU hours), the contractor should indicate the additional requirement. NIST cannot guarantee that resources in addition to those listed above can be made available.

The contractor shall be responsible for providing licensed copies of the necessary software that will be used for conducting the analyses. The software will be installed with the help of NIST. Access to the software shall be limited solely to the contractor.

Place of Performance

Work will be performed at Contractor's business location. Access to the NIST Gaithersburg site will be provided for reviewing WTC databases, documents, reports, drawings, photos, videos and other relevant information. The Contractor should allow for at least several days at NIST to review available information.

Applicable Documents

1. NIST Final Plan for the Investigation of the World Trade Center Disaster, found at Web site http://wtc.nist.gov

2. FEMA 403, World Trade Center Building Performance Study, May 2002, Chapter 5, found at FEMA Web site at http://www.fema.gov/library/wtcstudy.shtm

3. June 2004 Progress Report on the Federal Building and Fire Safety Investigation of the World Trade Center Disaster, Appendix L, found at Web site http://wtc.nist.gov

4. NIST NCSTAR 1-1 (Building description, structural and fire codes and standards, structural design criteria, fabrication, maintenance and the fuel systems)
5. NIST NCSTAR 1-1J (Design, installation, and operation of WTC 7 fuel systems)

6. NIST NCSTAR 1-3 (Steel mechanical properties), found at Web site http://wtc.nist.gov

Deliverables and Milestones/Schedule

The schedule and deliverable dates are relative to the notice to proceed (NTP).
The Contractor shall deliver the following products (time is estimated from the date of award of contract). The contract shall be completed in 10 months (38 weeks).

Item	Deliverables	Quantity	Performance Interval	Date
1	All WTC 7 structural models and input data developed under this contract	Electronic Data Files	24 weeks	24 weeks
2	Animation and graphics of the initiating event, failure sequence up to global collapse (including the vertical and horizontal progression of failures up to the point of global instability)	Electronic Data Files	24 weeks	24 weeks
3	Draft Report for all Tasks	Electronic Data Files	24 weeks	24 weeks
	NIST COTR and Lead WTC Investigator review		2 week	26 weeks
4	Revised Draft Report	Electronic Data Files	2 weeks	28 weeks (15 calendar days after receipt of comments from NIST COTR)
	NIST / AC Review		3 weeks	31 weeks
6	Final Report for Public Comment	Electronic Data Files	2 weeks	33 weeks (15 calendar days after NIST/ AC Review)
	Public Comment Period		3 weeks	36 weeks
7	Final Report	Electronic Data Files	2 weeks	38 weeks (15 calendar days after Public Review comments received)

All Contractor draft reports shall be delivered to NIST as specified above. NIST will review the draft and return it to the Contractor within fifteen (15) days after receipt with comments and instructions for a format to be used in the preparation of the final report. The Contractor shall incorporate the comments into a final report and furnish it to NIST within fifteen (15) days after receipt of NIST's comments, at each of the three levels of review: (1) COTR and Lead WTC Investigator , (2) NIST and NCST Advisory committee review (this is also described in the contract specification paragraph 36), and (3) public comment period.

In addition to regular communications with the Contractor, NIST shall meet with the Contractor at their facility for working meetings as needed. The contractor shall keep the COTR apprised of all progress, technical issues needing resolution, and results to date. The following review meetings are anticipated for monitoring the progress of the work:

Item	Schedule	Location	Date
1	Meeting to Start Project and review work plan	NIST	Notice To Proceed (NTP)
2	Progress Review Meeting	Contractor facility	12 weeks (estimate, to be determined at contract award)
3	Meeting to review completed work	NIST	24 weeks (estimate, to be determined at contract award)

The review meetings shall have a powerpoint presentation by the Contractor which presents progress relative to the planned schedule, significant technical issues needing resolution, and results to date.