Modeling Methodologies for Assessment of Aircraft Impact Damage to the World Trade Center Towers

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Abstract

The Federal Building and Fire Safety Investigation of the World Trade Center Disaster was recently completed by the National Institute of Standards and Technology (NIST). A critical component of the investigation was to analyze the aircraft impacts into the World Trade Center (WTC) towers to evaluate the impact-induced damage to the towers. This impact damage established initial conditions for the fire dynamics modeling, thermal-structural response, and collapse initiation analyses performed as part of the NIST investigation into the collapse of the WTC towers.

This paper presents the development of the WTC tower and aircraft models and associated analysis methodologies used to simulate the aircraft impact response. The analyses performed span the range from laboratory-scale material testing up to the global aircraft impact response of the WTC towers. Simulations were performed at various levels of refinement. Component analyses were performed using small portions of the aircraft and tower. In these analyses, components were modeled with a fine resolution to investigate the details of the initial impact and breakup behavior. Results from the component analyses were used to develop the simulation techniques required for the global analysis of the aircraft impacts. The global impact simulation techniques were aimed at reducing the overall global model size while maintaining fidelity in the impact response. The accuracy of the calculated aircraft impact damage was evaluated by comparison with observed impact damage to the towers.

1. Introduction

The objective of this project was to analyze the aircraft impacts into the World Trade Center (WTC) towers with a view to providing estimates of: (1) probable damage to structural systems, including the exterior walls, floor systems, and interior core columns; (2) aircraft fuel dispersal during the impact; and (3) debris damage to the interior tower contents. These debris damage estimates were needed for estimating the damage to fireproofing on the tower steels and the mechanical and architectural systems inside the towers. This project established the initial conditions for the fire dynamics modeling and thermal-structural response and collapse initiation analyses, performed as part of the NIST investigation into the collapse of the WTC towers. A complete description of the tasks required to perform the aircraft impact analyses is provided in Reference 1.

The models of the tower components were developed from the original design documents of the towers, using an electronic database of the primary structural components developed within the framework of the NIST investigation. The models of the aircraft components were developed from (1) documentary aircraft structural information, and (2) data from measurements on a Boeing 767 aircraft. The analyses were conducted using LS-DYNA software [2].

The analyses were conducted at various size scales and levels of complexity ranging from analyses of laboratory material tests to the global aircraft impact analyses, as illustrated in Figure 1. At each level of modeling, the required methodologies were developed for application to the next level of impact analyses. For example, the analyses of the laboratory material testing were used to validate the constitutive models as well as develop failure criteria for the materials at the appropriate mesh refinements used in subsequent component impact analyses. The component analyses were then used to develop further reductions in model refinement, needed for the larger subassembly and global impact simulations, while still capturing the same response characteristics and damage levels.

In the remainder of this paper describes the modeling methodologies used for simulating the aircraft impact response into the World Trade Center towers. The analyses begin with an evaluation of the material testing on recovered WTC steel and develop through increasing levels of complexity and scale up to the level of the global impact analyses of the aircraft into the towers. The primary challenge was to maintain appropriate impact damage and failure levels in the structural components as the model scale becomes increasingly larger and the model resolution in the individual components becomes, by necessity, progressively more coarse.

2. Analysis of Laboratory Material Testing

The analysis of the material testing performed on the recovered WTC tower steels was important for various reasons. Obviously it is important to correctly model the strength of the structures as they are loaded beyond their elastic limit. In addition, the laboratory material testing represents the primary area where controlled data was collected and can be used for validation. Finally, the material tests can be used for establishing the material failure criteria for various levels of mesh refinement.

The constitutive model used for the several grades of the tower steels was the Piecewise Linear Plasticity model. This model is sufficient to model the nonlinear dynamic deformation and failure of steel structures. A tabular effective stress versus effective strain curve can be used in this model with various definitions of strain rate dependence. The constitutive model parameters for each grade of steel were based on engineering stress-strain data obtained by testing of steel specimens from the towers. Strain-rate effects on the steel yield strength were included in the constitutive model for tower steels with the Cowper and Symonds rate effect model [3].

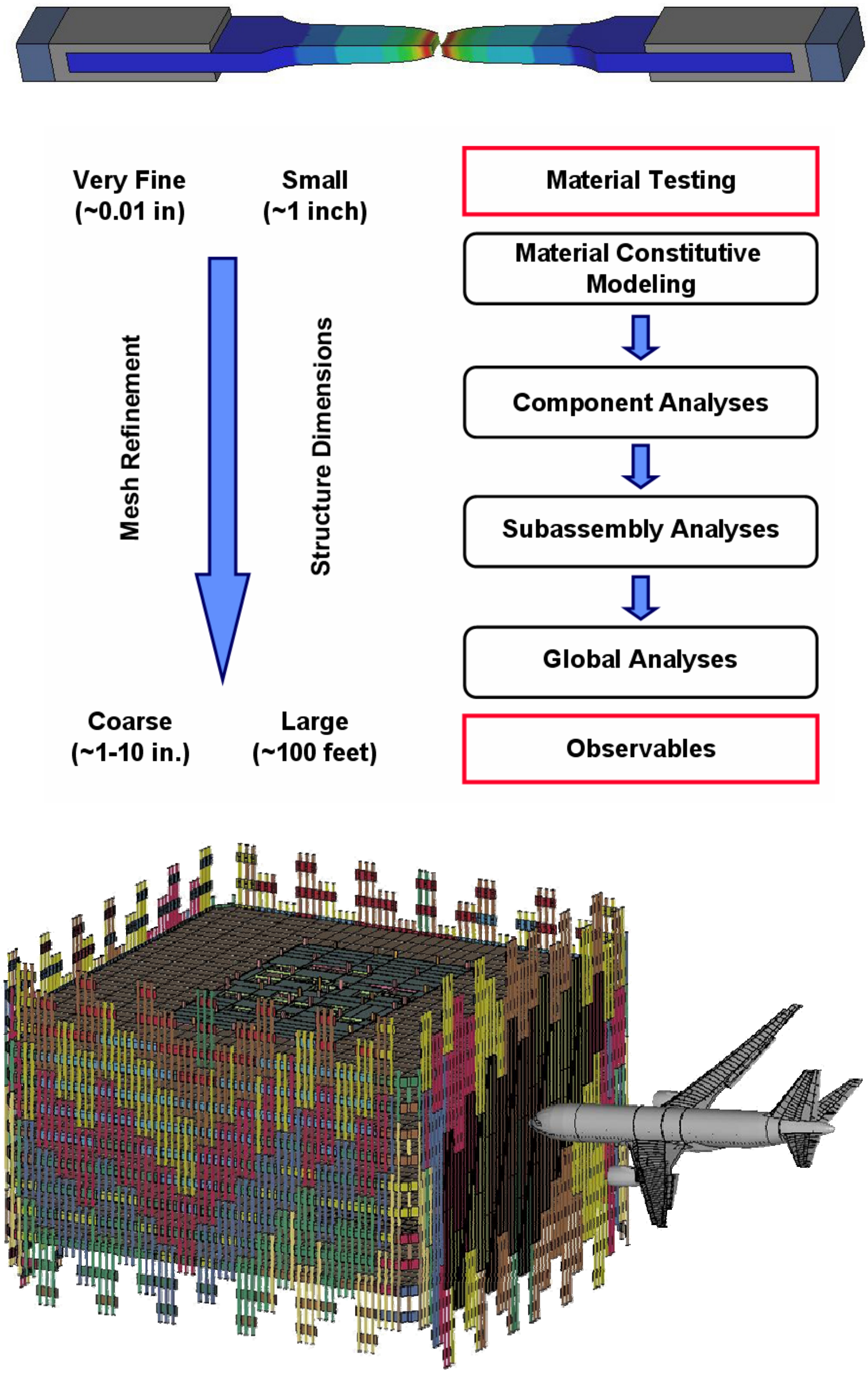


Figure 1. Range of analyses required from material testing to global impact response.

Finite element analyses of the test specimens were conducted to provide a validation that the constitutive model and failure parameters were defined accurately and that the model could reproduce the measured response for the test conditions. The analyses were performed with both fine and medium resolution brick element models to capture the nonlinear material behavior up to failure. The medium mesh resolution is similar to the mesh resolution used in the detailed component impact analyses. The finite element analysis of the material tests was also performed using a very coarse shell element model more appropriate for the reduced (coarse mesh) component models and global impact models. The various models of the material tensile specimens are shown in Figure 2.

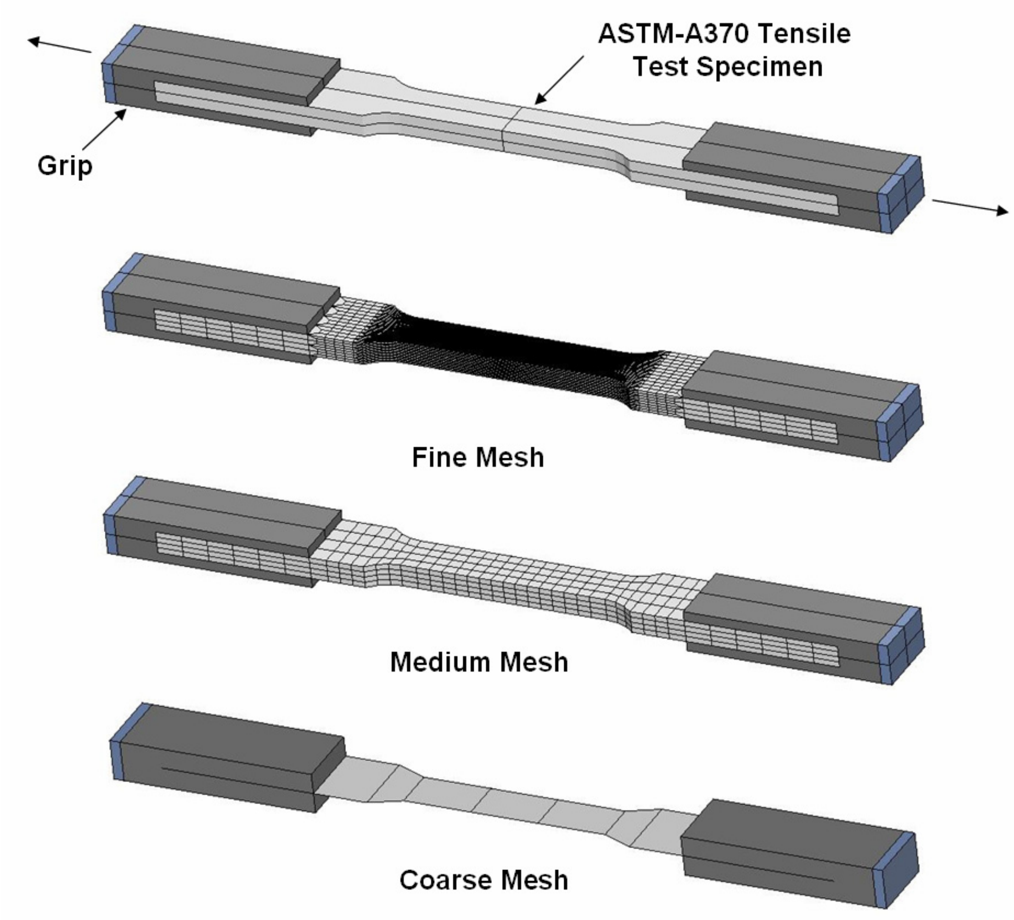


Figure 2. Mesh refinement study for material response and failure.

The analyses of the material tests clearly demonstrated the problem of mesh refinement effects in failure analysis. The calculated necking response in the fine and medium resolution models of the tensile specimen are shown in Figure 3. Both of the specimens begin the localization (necking) at the same level of elongation. However, as the necking develops, the comparison shows that for the same levels of overall specimen elongation and localization, the fine mesh more accurately captures the stress and strain gradients within the necked region. Thus, at the specimen elongation corresponding to failure, the peak strains in the fine mesh model are significantly higher and the strain-based failure criterion requires a higher failure strain for the corresponding finer mesh. The coarse shell element specimen model has a single element, and a single value of stress, that spans the entire gauge section. Here the element size is larger than the zone in which localization occurs and the model is not capable of reproducing the necking response.

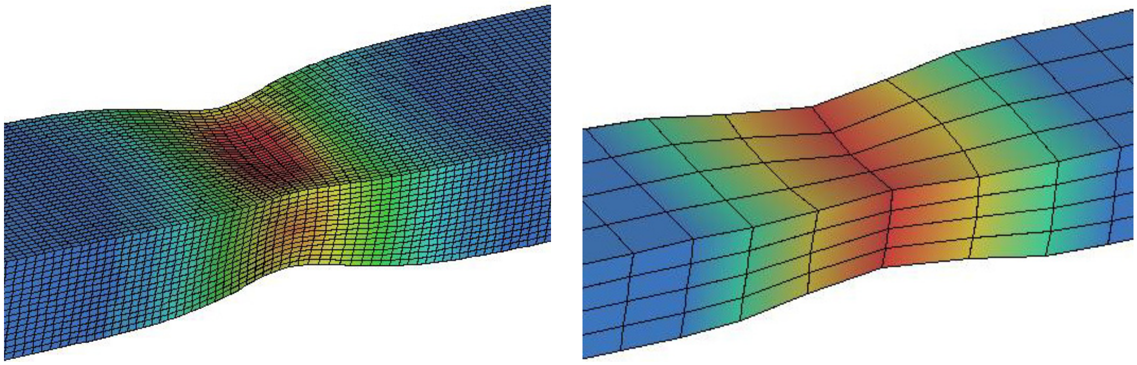


Figure 3. Mesh refinement study for material response and failure.

A comparison of the engineering stress strain curve calculated with the three different resolution models is shown in Figure 4. All of the models calculate the same stress-strain response up to the point of maximum stress at which time the localization initiates. At that time the stress levels out in the coarse model while the localization causes the stresses to decline in the medium and fine models. As the shape of the necked region continues to develop, the medium and fine mesh models eventually diverge as the medium mesh model is no longer capable of accurately resolving the local gradients in the necking region.

A simple critical plastic strain criterion was used to incorporate failure in the tower steel constitutive model. When this approach is applied to the analysis of the tensile tests for the 75 ksi steel, the values of the critical plastic strain for the coarse, medium, and fine mesh models were 18%, 56% and 100% respectively to obtain the same overall specimen elongation at failure. As a result, for each level of mesh refinement, approximately the same amount of energy is dissipated prior to failure. This approach was applied for all of the different grades of tower steel to obtain the corresponding failure strains used in subsequent component and global impact analyses.

3. Component Analyses

A series of component impact analyses were performed using models of core columns, exterior wall panels, and floor assemblies of the towers impacted by models of an aircraft wing section and an engine. The primary objectives of the component modeling were to develop (1) an understanding of the interactive failure phenomenon of the aircraft and tower components and (2) the simulation techniques required for the global analysis of the aircraft impacts into the WTC towers. The approach taken for component modeling was to start with finely meshed brick and shell element models of key components of the tower and aircraft structures, and progress to relatively coarsely meshed beam and shell element representations used in the global models. Other key technical areas were addressed in the component modeling included treatment of connections, and modeling of aircraft fuel. The results of the component analyses have been previously documented [2, 4]. The results of the wing section and exterior wall component impact simulations are described below to demonstrate the analysis methodologies used.

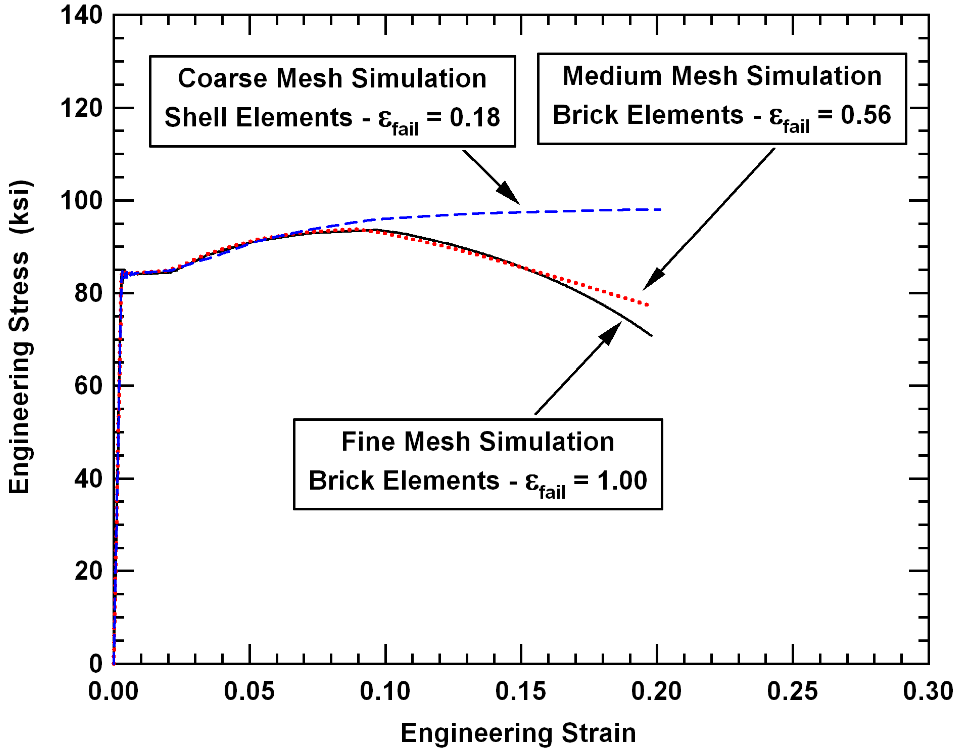


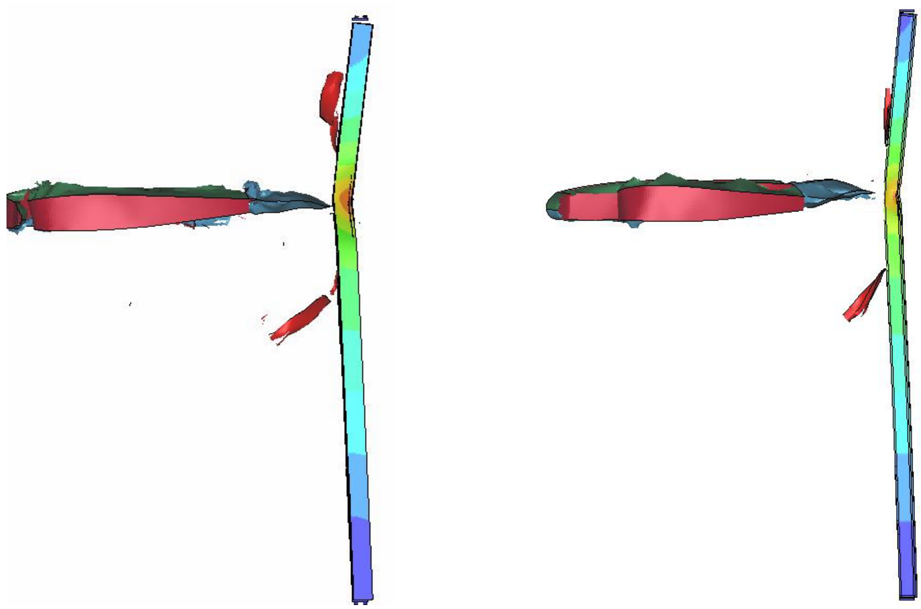
Figure 4. Mesh refinement study for material response and failure.

Exterior column impacted with an empty wing

The objective of this component analysis was to develop a model of the exterior columns with a coarse mesh that could be used in the global impact analyses and still capture the impact damage properly. The analysis used an empty wing section impacting an exterior wall column of the tower at a speed of 470 mph (210 m/s).

The exterior column model was constructed entirely of 55 ksi (379 MPa) steel, and the spandrel plates were modeled with 42 ksi (290 MPa) steel. Both a model with a fine mesh of brick elements and a model with a coarser mesh of shell elements were developed. These models included a specific description of the weld geometry. In the fine brick element model, the failure strain for the base metal, weld metal, and heat- affected zone were all set at a uniform plastic strain of 64 %, corresponding to the base metal ductility. Failure strains in the coarse shell element models were then adjusted until a similar impact damage and failure mechanism were obtained.

The calculated impact response is shown in Figure 5. The column model on the left has the fine mesh of brick elements and the column model on the right has the coarse mesh of shell elements. The overall response was similar in both magnitude and damage mode. The reduction in model refinement resulted in a significant reduction in run time from over 600 min to 9 min. This comparison demonstrated the significance of the mesh refinement for capturing local stress and strain concentrations, and the resulting effect on the impact response.



Fine brick model **Coarse shell model**

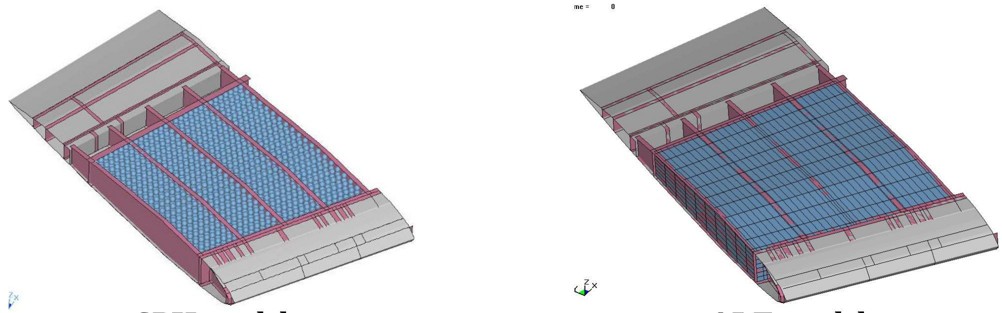
Figure 5. Comparison of an exterior column response to an aircraft wing impact

Impact of an aircraft wing with fuel into the exterior wall

A significant portion of the weight of a Boeing 767 wing is the weight of fuel in its integral fuel tanks. Upon impact, this fuel was responsible for large distributed loads on the exterior columns of the WTC towers and subsequently on interior structures, as the fuel flowed into the building. Modeling of the fluid-structure interaction is necessary to predict the extent of damage as well as the fuel dispersion within the building to help establish the initial conditions for the fire dynamics modeling.

A number of approaches to solving fluid-structure interaction problems are available in LS-DYNA. One approach is the standard Lagrangian finite element analysis with erosion, where the fuel is modeled using a deformable mesh. This approach accounts for the inertial effects of the initial fuel impact, but does not accurately simulate the subsequent fuel dispersion due to limitations on mesh distortion and/or mass loss from element erosion. The Arbitrary-Lagrangian-Eulerian (ALE) method was developed as a good approach to solving fluid and solid material interaction. With this methodology, fluids are advected through a non-deformable mesh, which allows for large deformation of these materials without mass loss. Solid materials are modeled with a moving Lagrangian mesh. With ALE, both mesh types can interact. An alternative approach is to use mesh-free methods such as Smoothed Particle Hydrodynamics (SPH). SPH modeling for fuel effects has the advantage of a smaller mesh size and potentially much faster run times than ALE analyses. Both ALE and SPH methods were applied to the analysis of fuel impact and dispersion and are compared in this study.

A small wing segment was used for performing component level analyses of the wing with fuel. The segment was considered to be completely filled with fuel (approximately 850 gal, representative of four fuel bays just outboard of the engine on a Boeing 767). Figure 6 shows the wing section model with an SPH and ALE mesh for the fuel, shown in blue. The fuel was modeled with 6,720 SPH fuel particles and 110,825 ALE elements for the fuel and surrounding air region, shown in Figure 7. The impacted structures were two exterior wall panels as shown in the figure.



SPH model **ALE model**

Figure 6. SPH and ALE fuel in a Lagrangian wing segment model

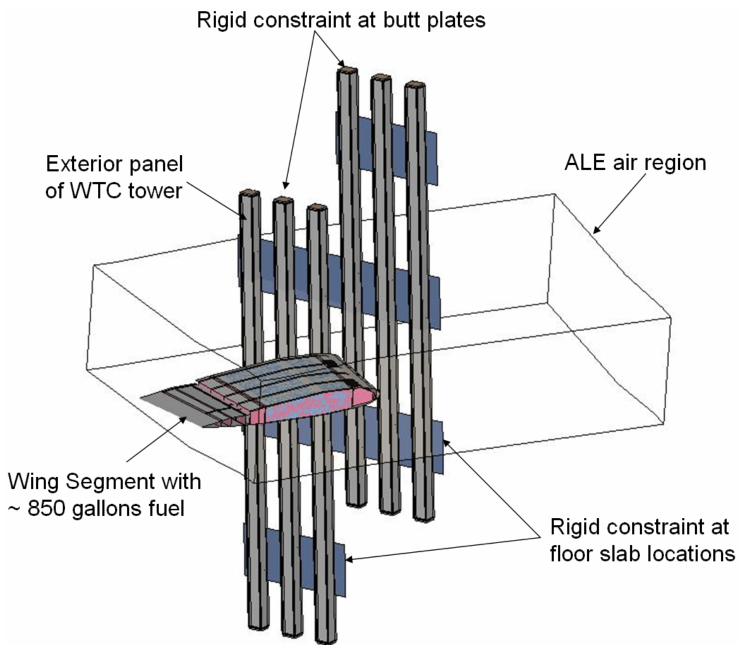
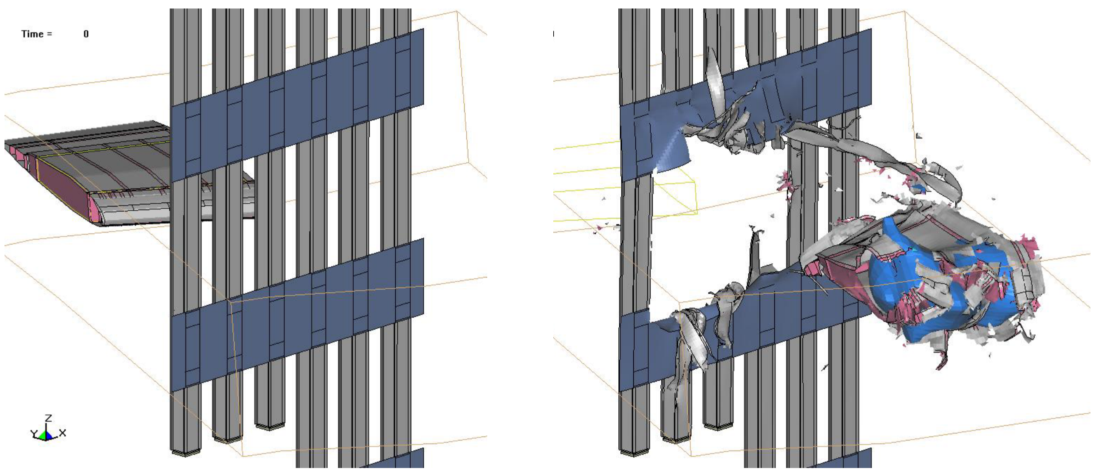


Figure 7. Wing segment, fuel, and exterior panel configuration

An ALE mesh surrounding the wing segment and the panels was needed for the fuel to flow into. In ALE analyses, material is advected from one element to the next so that a mesh is needed for initially "empty" regions. In this case, this mesh was filled with stationary air to interact with the fuel.

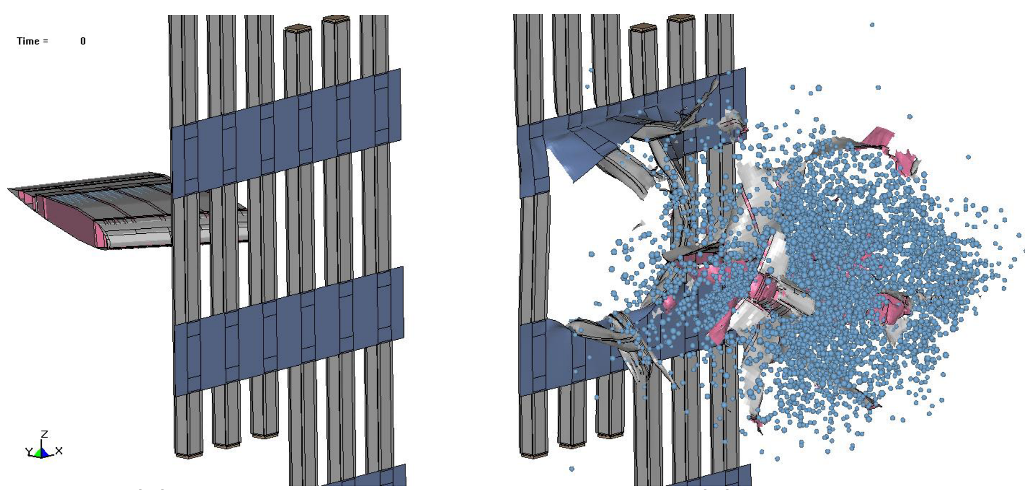
The wing segment trajectory was a normal impact on the exterior wall at mid-height between spandrels with a speed of 500 mph (224 m/s). The wing was oriented with no pitch, yaw, or roll. The leading edge therefore impacted the panels with the sweep angle of the wing relative to the fuselage. The two exterior panels were constrained rigidly at the butt plates and at the floor slab locations.

Results of the impact analysis of the wing section using the ALE and SPH approaches are shown in Figures 8 and 9, respectively. In both cases, the columns of the exterior panels were completely destroyed by the impact. Additional analyses (not reported in this paper) showed that a normal impact of the exterior wall by an empty wing segment produced significant damage to the exterior columns but not necessarily complete failure. A comparison of the fuel dispersion and wing break-up predicted by the two fuel modeling approaches indicates that the SPH modeling approach predicted larger fuel dispersion and wing break-up than the ALE approach. Without experimental data, it is difficult to evaluate which method provides a more accurate solution.



t = 0.0 s **t= 0.04 s**

Figure 8. Impact response of a wing section laden with fuel modeled using ALE.



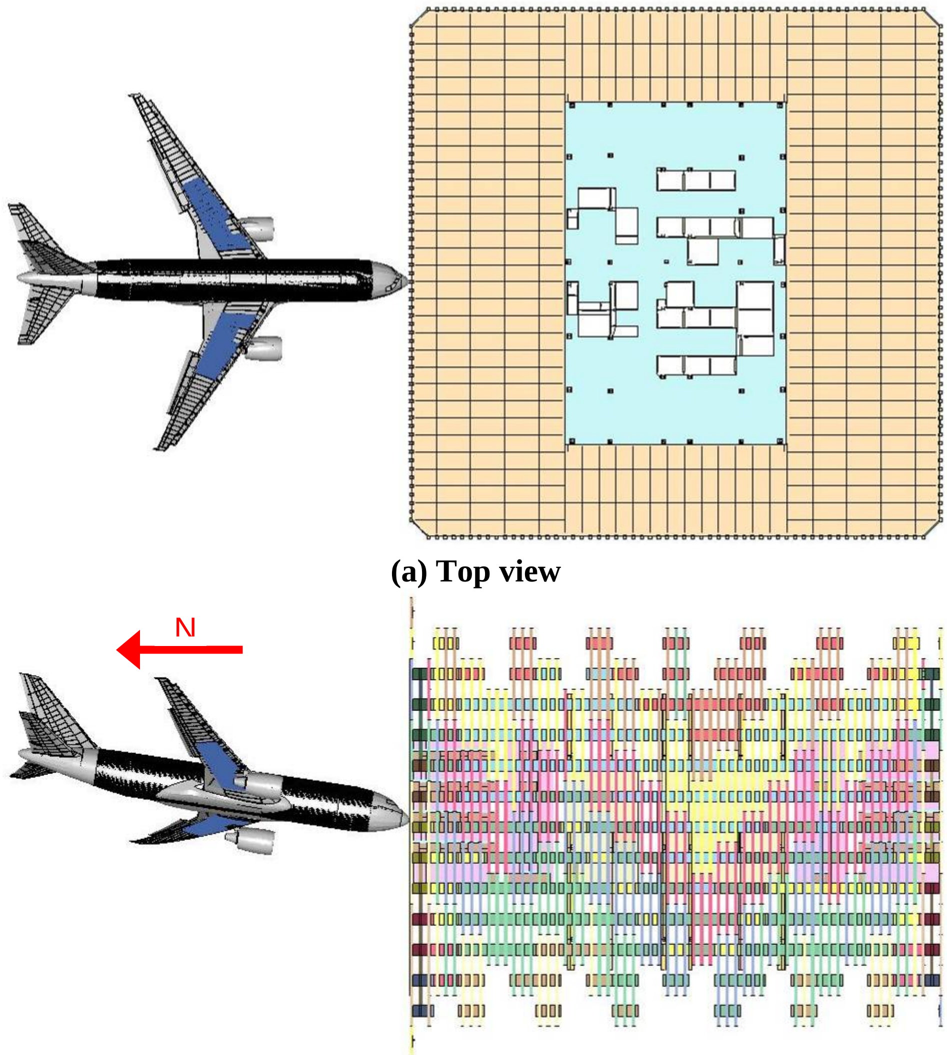
t = 0.0 s **t= 0.04 s**

Figure 9. Impact response of a wing section laden with fuel modeled using SPH.

Run times from these component analyses indicated that the SPH method was more practical for global impact analyses. The SPH model ran about 10 times faster than the ALE method as it required a smaller mesh and did not need re-zoning after each time step, as was the case for the ALE method. In addition, the ALE method required a mesh for both the fuel region and the air zone into which the fuel could flow. The SPH method was therefore selected as the modeling technique for the global analyses.

4. Global Impact Analyses

The combined aircraft and tower model for the base case WTC 1 global impact analysis is shown in Figure 10 where the fuel in the wing tanks is shown in blue. The base case analysis used the best estimate for all of the tower, aircraft, and impact parameters. The model has approximately 2.3 million nodes and the analysis was performed for a 0.715 second duration following initial impact of the aircraft nose with the north exterior wall. The analysis was performed on a computer cluster using twelve 2.8 GHz Intel Xeon processors, each on a separate node of the cluster and the run time was approximately two weeks. The progress of the global impact simulations was monitored on average every two days. The calculations were terminated when the damage to the towers reached a steady state and the motion of the debris was reduced to a level that was not expected to produce any significant increase in the impact damage. The residual kinetic energy of the airframe components at the termination of a global impact simulation was typically less than one percent of the initial kinetic energy at impact.



(a) Top view

(b) Side view

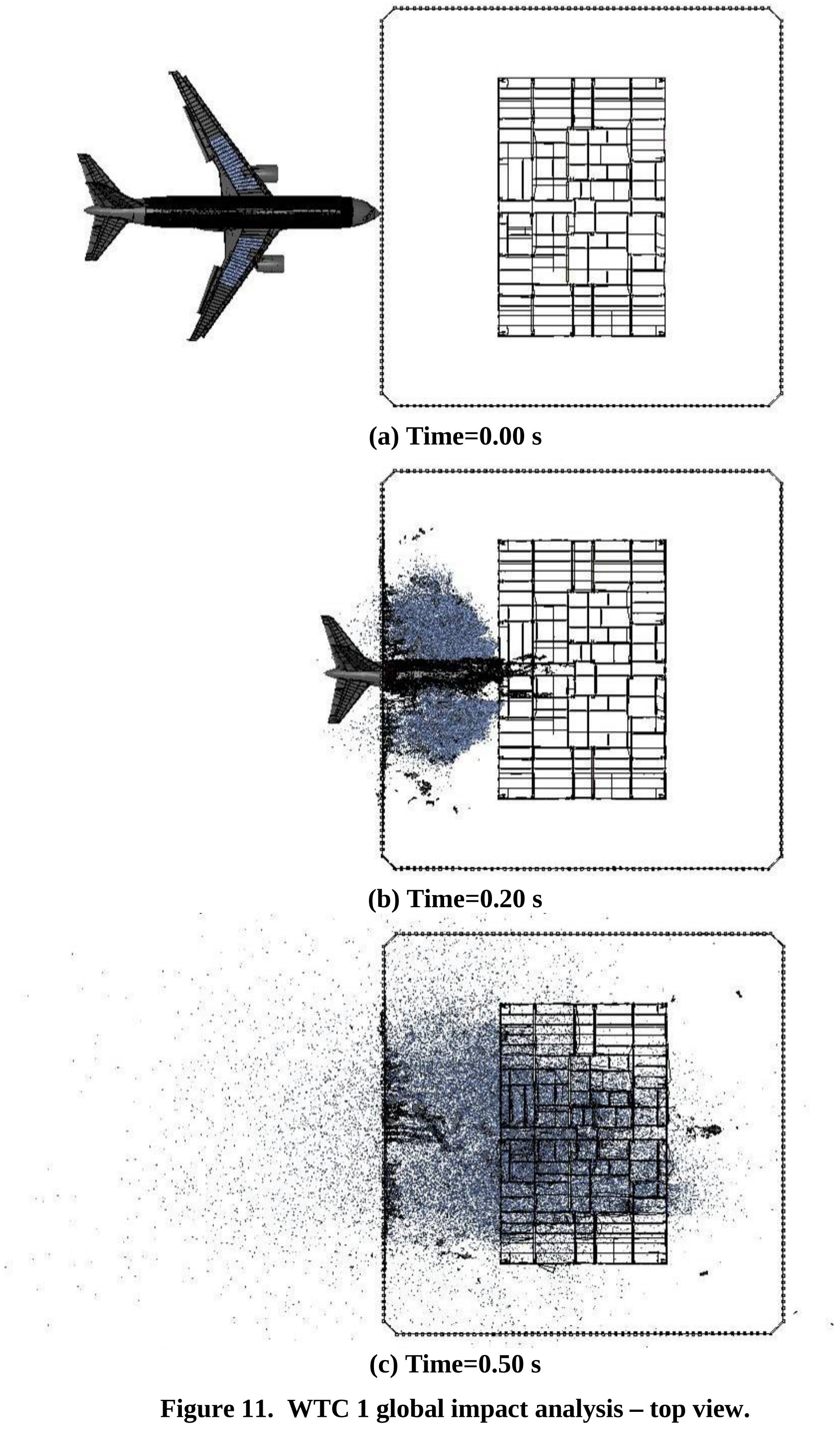
Figure 10. WTC 1 global impact model.

A top view of the base case WTC 1 global impact response is shown in Figure 11. In the figure, the tower interior contents and floor structures were removed from view, and the tower structures were shown as transparent so that the impact response in the tower interior could be seen. The aircraft impact response was dominated by the impact, penetration, and fragmentation of the airframe structures. The entire aircraft fully penetrated the tower at approximately 0.25 s. The fuselage structures were severely damaged both from the penetration through the exterior columns and the penetration of the 96th floor slab that sliced the fuselage structures in half. The downward trajectory of the aircraft structures caused the airframe to collapse against the floor, and the subsequent debris motion was redirected inward along a more horizontal trajectory parallel to the floor. The downward trajectory of the aircraft structures transferred sufficient vertical load such that the truss floor structures on the 95th and 96th floors collapsed in the impact zone.

The aircraft was severely broken into debris as a result of the impact with the tower as shown in Figure 12. At the end of the impact analysis, the aircraft was broken into thousands of debris fragments of various size and mass, as shown in Figure 16(b). A closer inspection of the debris field shows that larger fragments still existed for specific components such as the engines. Both engines had significant impact damage with one of the engines broken into two large pieces. At the end of the simulation, the port engine was still inside the core, and the starboard engine was roughly one third of the distance from the core to the south exterior wall.

The calculated damage to the exterior wall was significant for two reasons: (1) the exterior wall carried a significant portion of the load in the tower, and the degradation in exterior wall strength was important for the collapse analyses, and (2) the exterior wall was the one structural system for which direct visual evidence of the impact damage was available. Therefore, the comparison of the calculated and observed exterior wall damage could provide a partial validation of the analysis methodologies used in the global impact analyses.

Damage to the north exterior wall calculated in the base case WTC 1 global impact analysis is shown in Figure 13. This damage was compared with a schematic of observed damage developed from inspections of the video and photographic data collected on the tower after impact. The calculated and observed damage in the impact damage zone were in good agreement. The exterior wall completely failed in the regions where the fuselage, engine, and fuel-filled wing section impacted the tower. Damage to the exterior wall was observed out to the wing tips, but the exterior columns were not completely failed in the outer wing and vertical stabilizer impact regions. Failure of the exterior columns occurred both at the bolted connections between column ends and at various locations in the column, depending on the local severity of the impact load and the proximity of the bolted connection to the impact. The agreement of both the mode and magnitude of the impact damage serves to partially validate the modeling methodologies used.



(a) Time=0.00 s

(b) Time=0.20 s

(c) Time=0.50 s

Figure 11. WTC 1 global impact analysis – top view.

(a) Aircraft structure (time=0.00 s)

(b) Aircraft debris field (time=0.715 s)

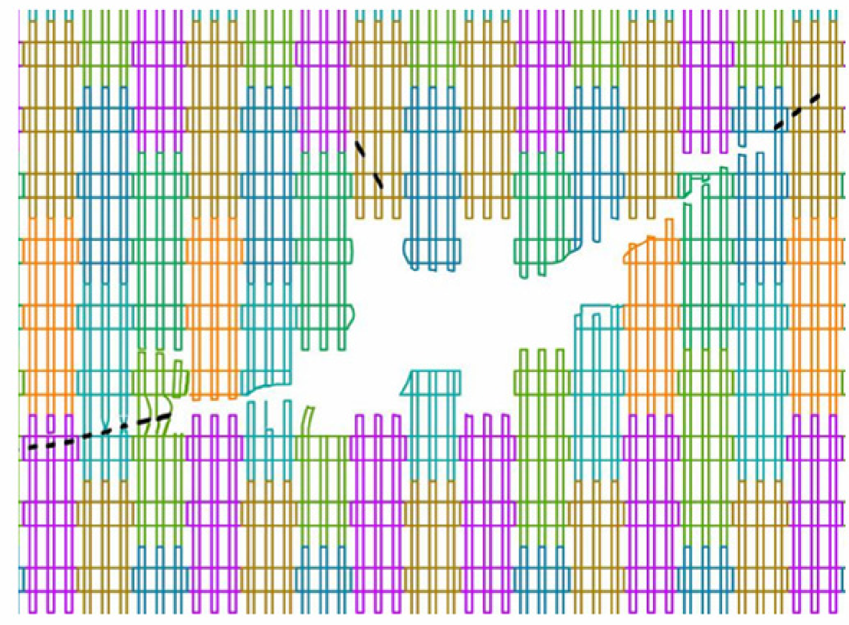
Figure 12. Breakup of the aircraft and resulting Debris field.

5. Summary

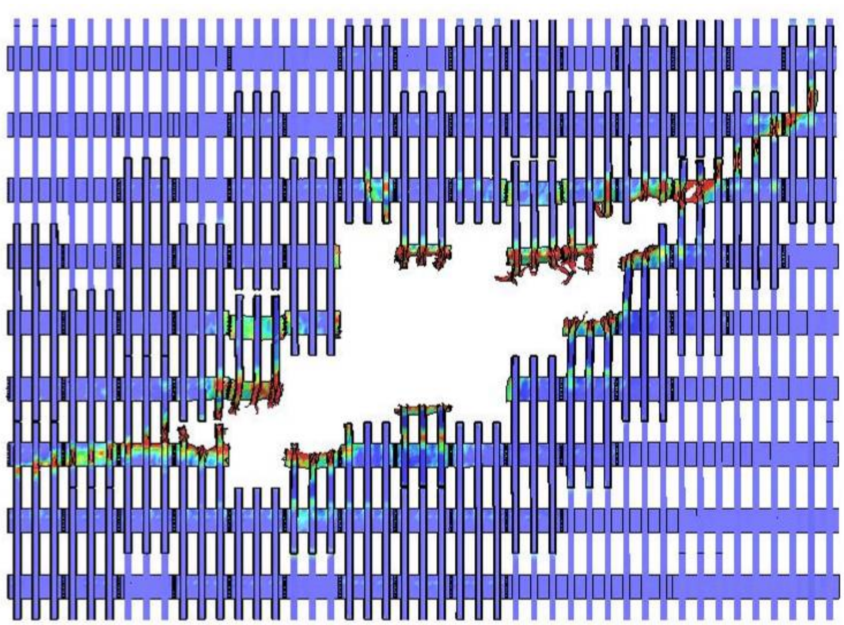
Detailed analyses were performed to assess the aircraft impact damage for the World Trade Center (WTC) towers. The analyses provided significant information about: (1) probable damage to structural systems, including the exterior walls, floor systems, and interior core columns; (2) aircraft fuel dispersal during the impact; and (3) debris damage to the interior tower contents. The analyses were conducted using LS-DYNA.

To develop the required methodologies, analyses were conducted at various size scales and levels of complexity ranging from analyses of laboratory material tests to the global aircraft impact analyses. At each level of modeling, the required methodologies were developed for application to the next level of impact analyses. Component analyses were used extensively to address issues such as model refinement, modeling of connections, and analysis of the aircraft fuel.

Three different numerical techniques were investigated for modeling impact effects and dispersion of fuel inside the wings: (1) standard Lagrangian finite element analysis with erosion, (2) Smoothed Particle Hydrodynamics (SPH) analysis, and (3) Arbitrary-Lagrangian-Eulerian (ALE) analysis. Of these approaches, SPH analyses were adopted for modeling fuel in the global impact analysis due to computational efficiency.



(a) Schematic of actual damage



(b) Calculated damage

Figure 13. External damage from the WTC 1 aircraft impact.

The final impact damage estimates were validated as much as possible by comparison to observables. The observables available to help validate the global impact analyses included the following:

- Damage to the building exterior (exterior walls and floors in the immediate vicinity of the impact) documented by photographic evidence.
- Aircraft debris external to the towers (landing gear for WTC 1 and landing gear and engine for WTC 2) as documented by photographic evidence.
- Eyewitness accounts from survivors who were inside the towers (blocked or passable stairwells).
- Observed failure modes of exterior columns impacted by the aircraft and recovered from the wreckage.

Not all of these observables were perfectly matched by the simulations due to the uncertainties in exact impact conditions, the imperfect knowledge of the interior tower contents, the chaotic behavior of the aircraft break up and subsequent debris motion, and the limitations of the models. In general, however, the results of the simulations matched the observables sufficiently well to support the methodologies that were used.

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